REPORT f3 2018:13

LONG-TERM SUSTAINABILITY ASSESSMENT OF FOSSIL-FREE FUEL PRODUCTION CONCEPTS

Report from a project within the collaborative research program *Renewable transportation fuels and systems*

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THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This project has been carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 42402-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities
- Carries through system-oriented research related to the entire renewable fuels value chain
- Acts as national platform stimulating interaction nationally and internationally.

f3 partners include Sweden's most active universities and research institutes within the field, as well as a broad range of industry companies with high relevance. f3 has no political agenda and does not conduct lobbying activities for specific fuels or systems, nor for the f3 partners' respective areas of interest.

The f3 Centre is financed jointly by the centre partners and the region of Västra Götaland. f3 also receives funding from Vinnova (Sweden's innovation agency) as a Swedish advocacy platform towards Horizon 2020. Chalmers Industriteknik (CIT) functions as the host of the f3 organization (see www.f3centre.se).

This project was carried out during the period 1/9 2016 – 31/3 2018. The participating research groups were Energy Sciences at Luleå University of Technology (initially represented by Åsa Kastensson, replaced by Joakim Lundgren as of January 2017), Environmental and Energy Systems Studies at Lund University (represented by Pål Börjesson), Environmental Systems Analysis at Chalmers (represented by Matty Janssen) and Industrial Energy Systems Analysis at Chalmers (represented by Simon Harvey, who was also the project leader).

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SUMMARY

The number of possible combinations of feedstock, feedstock pre-treatment, and downstream processes for large-scale production of different types of biofuel is substantial. Different production routes will obviously perform very differently with respect to profitability and carbon footprint. Furthermore, large-scale production of biofuels requires substantial strategic investment decisions, requiring a prospective assessment approach. Evaluation of future biorefinery concepts using today's conditions can be heavily misleading, and it is therefore essential that possible future conditions and related uncertainties are taken into account. This work explores methodological choices and assumptions of Techno-Economic Assessment (TEA) and Life Cycle Assessment (LCA) methods and tools used in four research groups in Sweden for assessing the long-term economic and carbon footprint performance of large future biorefinery concepts.

The report presents an in-depth analysis of the methods and tools used in the participating groups, and clearly establishes the need for increased collaboration and data exchange between biorefinery process developers, value chain modellers, TEA and LCA practitioners and large-scale energy and material system modellers. The work presented constitutes a significant step in this direction by clearly establishing the potential strength of prospective TEA and LCA in combination with scenarios describing possible future developments of the background energy system in which future biofuel production systems will operate. The report presents new results for one of the bio-methane production routes investigated in the "METDRIV - Methane as vehicle fuel – a well-to-wheel analysis" study conducted by Börjesson et al (2016) with respect to energy, greenhouse gas emissions (GHG) and cost performance. The input data used in the original METDRIV study were based on average prices/costs and GHG emission factors valid at the time of the study. In this work, new input data is adopted that reflects possible energy market development pathways generated by the ENPAC energy market scenario tool developed at Chalmers. For the selected production route, the results show that assumptions for costs and greenhouse gas emission factors related to increased use of biomass are of utmost significance, and that there is a clear need for further work in this area.

Finally, the report discusses some of the major challenges that remain to be addressed when developing scenarios for the "background" energy system to be used in prospective assessment studies of future biorefinery concepts:

- Handling the possible consequences of future limited biomass availability on biomass feedstock prices and emission factors.
- Handling future development of the electric power grid, as well as other large-scale grid energy systems (e.g. district heating) in a carbon-constrained world
- Integration issues: large-scale biorefinery concepts are likely to be co-located at existing industrial sites, which will also evolve in reaction to policy instruments, thereby affecting opportunities for integration of material and energy flows.

SAMMANFATTNING

Det finns ett stort antal möjliga kombinationer av råvaror, förbehandlingsmetoder och omvandlingstekniker för storskalig produktion av biodrivmedel. De olika produktionsvägarna har väldigt olika prestanda vad gäller lönsamhet och koldioxidutsläpp. Storskalig produktion av biodrivmedel kräver omfattande strategiska investeringsbeslut, vilket kräver avancerade framåtblickande utvärderingsmetoder. Att utvärdera framtida bioraffinaderikoncept med dagens förutsättningar kan leda till felaktiga slutsatser, och det är därför viktigt att möjliga framtida förutsättningar och de associerade osäkerheterna beaktas. Detta arbete belyser de metodologiska val och antagande av de metoder för teknoekonomiska och livscykelanalyser som används i fyra centrala svenska forskargrupper för utvärdering av de långsiktiga ekonomiska och klimatmässiga prestanda för framtida storskaliga bioraffinaderikoncept.

Utöver en fördjupad analys av de metoder och verktyg som används inom de respektive forskargrupper, belyser rapporten behovet av utökat samarbete och utbyte av data mellan bioraffinaderiprocessutvecklare, värdekedjeanalytiker, teknoekonomiska analytiker och livscykelanalytiker samt energisystemmodellerare. Det arbete som presenteras utgör en betydande insats i denna riktning genom att belysa den potentiella styrkan av att analysera bioraffinaderikoncept med framåtblickande teknoekonomiska metoder och livscykelanalysmetoder i kombination med scenarier som beskriver möjliga framtida utvecklingsvägar för bakgrundsenergisystemet. Rapporten innehåller nya resultat för en fallstudie, processvägar för storskalig produktion av biometan som utvärderades med avseende på energi-, växthusgas-och kostnadsprestanda i projektet METDRIV (se Börjesson et al, 2016). Beräkningsdata som användes i METDRIV-studien baserades på priser, kostnader och växthusgasutsläppsfaktorer som var giltiga när studien genomfördes. De nya resultaten räknades fram med ny inputdata som speglar möjliga framtida utvecklingsvägar för energimarknaden, framtagna med hjälp av verktyget ENPAC utvecklat på Chalmers. I denna fallstudie visar resultaten tydligt att med framåtblickande metoder fås stora förändringar i både klimatpåverkan och ekonomi jämfört med tidigare studie. Ett exempel är antaganden avseende hur råvarukostnader och växthusgasutsläppsfaktorerna berörs av en framtida utökad användning av biomassa.

Avslutningsvis diskuterar rapporten några stora utmaningar som måste tas hänsyn till vid framtagning av framtida scenarier för bakgrundssystemet och som är viktiga i framåtblickande utvärderingsstudier av storskaliga bioraffinaderier:

- Hur påverkas bioraffinaderiers råvarukostnader och tillhörande utsläppsfaktorer när tillgång till biomassa begränsas i framtiden?
- Hur kommer elsektorn och andra stora ledningsburna energisektorer att utvecklas i en värld med omfattande krav på minskat utsläpp av växthusgaser?
- Integrationsaspekter: storskaliga bioraffinaderier kommer troligtvis att samlokaliseras med befintliga industrier, som kommer också att ändras p g a kraftigt ändrade styrmedel, vilket kommer att påverka förutsättningar för integration av materiella- och energiflödena.
  Ovanstående områden är viktiga exempel på fortsatt forskningsbehov.

CONTENTS

1 INTRODUCTION

1.1 PROJECT PARTICIPANTS

This report explores the complementarity of the methods and tools used in four significant research groups in Sweden for assessing the long-term sustainability of fossil-free fuel production concepts. Before presenting the background, aims and objectives of the work, we first provide a brief overview of the participating research groups' research profiles of relevance for this work, see Figure 1-1.

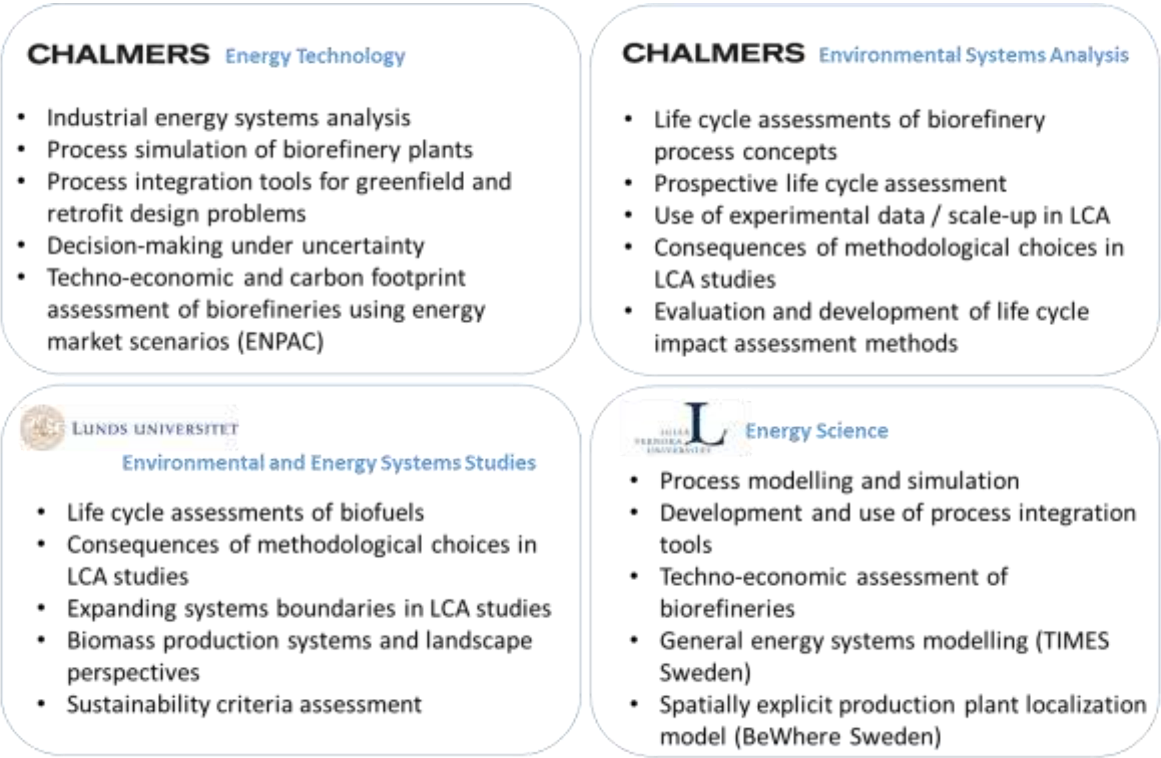

Figure 1-1 Research profiles of the participating research groups.

1.1.1 Energy Science at LTU (Luleå University of Technology)

The Division of Energy Science at LTU conducts energy systems analysis studies across a wide range of different system boundaries. There is a strong focus on process modelling (using process simulation software such as Aspen Plus), development and application of process integration tools as well as on techno-economic assessment (TEA) of various production systems. The technical analyses typically include material and energy balance calculations, production yields and energy efficiency calculations. In the economic analyses, profitability under existing as well as future forecasted energy market conditions is usually evaluated. Most studies adopt an "n^{th} plant" approach using cost and scale factors. More general system studies are also carried out involving the development and use of TIMES Sweden and the spatially explicit production plant localization model (BeWhere Sweden). In these models, different roadmap scenarios are used to consider future energy market conditions, energy demands, available resources etc. Finally, the Energy Science group has well-established collaboration with the International Institute for Applied Systems Analysis, which enables them to leverage their own expertise by providing input to IIASA's large system analysis tools that are able to optimize supply chains and eco-systems accounting for a number of ecological and economic objectives.

1.1.2 Environmental and Energy Systems Studies at LU (Lund University)

The Environmental and Energy Systems Studies (EESS) group focuses on multi-disciplinary studies of energy systems. Different complementary assessment tools and approaches are used in the research depending on the scope of the analyses. Assessments of the long-term life-cycle sustainability of bioenergy and biofuel systems have been a core research area for more than two decades. Life cycle assessment (LCA) tools are commonly used, but critical assumptions and methodological choices (system boundaries, allocation principles, time perspectives, geographical locations, etc.) are scrutinized. For example, several studies have been performed calculating the life cycle GHG emissions and environmental performance of Swedish biofuels from a broad systems perspective, and according to actual legislations regarding sustainability criteria. New research activities focus increasingly on broadening the systems perspective by combining LCAs of biofuels systems and related surrounding systems in new and innovative ways in so called “expanded LCAs”. Thus, the EESS group works continuously with methodological development within the energy and environmental systems studies area.

1.1.3 Environmental Systems Analysis, Chalmers

The Division of Environmental Systems Analysis at Chalmers focuses on the analysis of industrial production systems of various kinds. LCA studies have been performed for a variety of production systems that make use of bio-based raw materials (agricultural and forest biomass, pulp and paper waste streams, etc.) and produce not only energy and fuels, but also chemicals and materials. The focus has been on the assessment of technologies that are currently in development for the production of these types of products. For example, LCAs have been performed for an innovative technology for the production of ethanol from both agricultural and forest biomass. By modelling this technology in a future setting, by for instance adjusting the energy mix in the background system according to projections, an assessment can be made of how this technology will perform once it reaches maturity. The methodological implications for doing such "prospective" LCAs are currently a focus for research in order to use LCA as a tool for guiding technology development from a life cycle environmental point-of-view.

1.1.4 Industrial Energy Systems Analysis, Chalmers

The Industrial Energy Systems Analysis (IESA) group at Chalmers has a long tradition of investigating process integration opportunities in industrial energy systems. Process integration (PI) is an important approach for identifying opportunities to achieve substantially increased energy efficiency and reduced GHG emissions for industrial processes, including large-scale production of biofuels in integrated biorefinery processes. Profitability and net GHG emissions reduction potential of related investments are assessed by quantifying their impact within a future energy market context. Future energy market conditions are, however, subject to significant uncertainty. The IESA group has developed methods to handle decision-making subject to such uncertainty. Candidate investments are assessed using different scenarios generated using an in-house tool (ENPAC) that include future fuel prices, energy carrier prices, as well as indicative values of GHG emissions associated with important energy flows related to industrial plant operations. By assessing profitability for different cornerstones of energy market conditions, robust investment options can hopefully be identified, i.e. investment decisions that perform acceptably for a variety of different energy market scenarios. This approach is combined with process simulation tools such as Aspen Plus and process integration tools, mainly based on Pinch Technology.

1.2 LARGE-SCALE PRODUCTION OF BIOFUELS - BACKGROUND

There is currently a wide agreement within the scientific community about the urgent need to curb anthropogenic emissions of greenhouse gases to the atmosphere. In their most recent Assessment Report (AR5) (IPCC, 2014), the Intergovernmental Panel on Climate Change states clearly that

> *Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems.*

The IPCC report presents a number of mitigation scenarios that limit CO_2-equivalent concentrations to low levels (about 450 ppm CO_2-eq, likely to limit warming to 2°C above pre-industrial levels). All scenarios point to deep decarbonization, increased efficiency, and increased use of biomass feedstock in a number of sectors. The importance of well-designed systemic and cross-sectoral mitigation strategies is also clearly emphasized.

Sweden's energy and climate policies are in line with the IPCC's recommendation. In June 2017, the Swedish Parliament took a decision on the introduction of a climate policy framework for Sweden containing new climate goals, a Climate Act and plans for a climate policy council. The new climate goals stipulate that greenhouse gas emissions from the domestic transportation sector (excluding air travel) must decrease by at least 70% by 2030, compared with 2010. Possible scenarios for reaching this target have been presented in a number of policy documents, most recently the reports presenting the proposals of the Cross-Party Committee on Environmental Objectives (SOU 2016:47) which provided the basis for the new climate policy framework. All such policy documents underline the necessity of substantial simultaneous changes in a number of areas, including societal planning (to decrease the transportation requirements), improved efficiency (to decrease the energy requirements per unit of transportation service provided) and increased use of renewable fuels (both in the form of renewable electricity and biofuels).

For large-scale production of biofuels, the number of possible combinations of feedstock, feedstock pre-treatment, and upgrading to biofuel is substantial. There are many different types of biofuel, and many different possible locations for their production, including stand-alone plants as well as integrated plants at existing industrial sites equipped to handle large flows of biomass material. An overview of a number of such production routes is shown in Figure 1-2. Biofuel production routes based on forestry residues are considered by many experts as the most relevant option for Sweden, thus the focus of this report will be on this feedstock, unless otherwise noted.

Different biofuel production routes obviously perform very differently with respect to profitability and carbon footprint. Such aspects have been studied in detail by many authors, including work conducted within the f3 centre (see e.g. Ahlgren *et al* (2013), Anheden *et al* (2016) and Jansson *et al* (2013)). Large-scale production of biofuels requires substantial industrial strategic investment decisions that take into account a large number of future aspects and uncertainties, requiring a prospective assessment approach. For example, the carbon footprint impact related to implementation of a given production route will depend on the energy mix in the surrounding energy system, which will vary over time, as shown by e.g. Jönsson et. al (2013) and Joelsson and Gustavsson (2012).

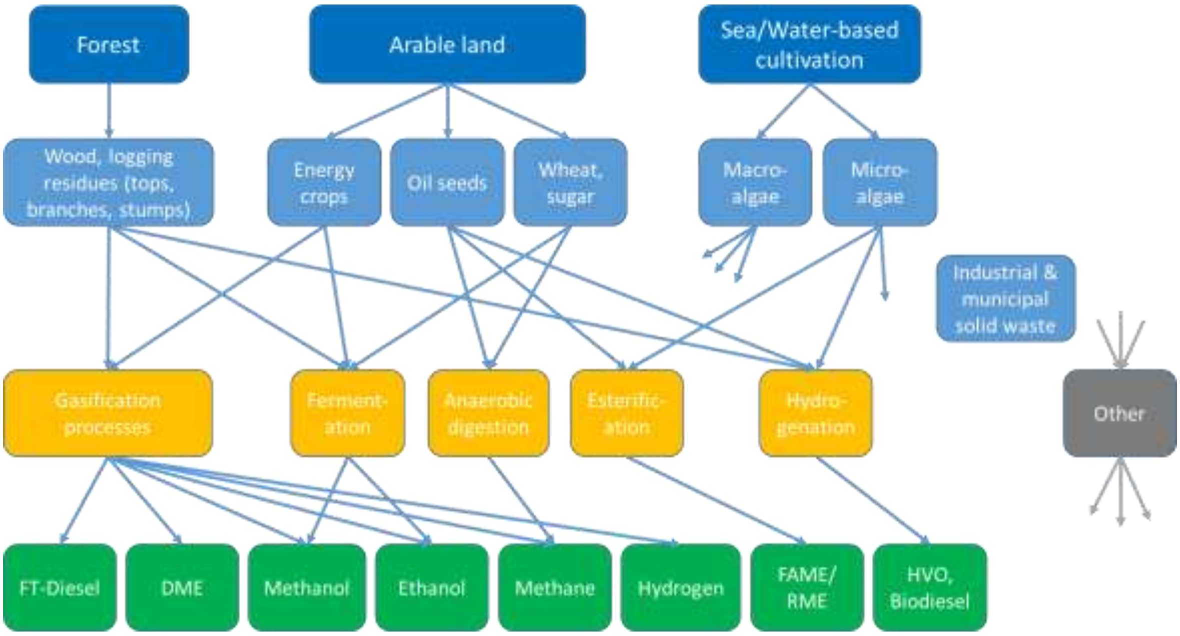

Figure 1-2 Overview of feedstocks and conversion pathways for biofuel production. Adapted from Börjesson *et al* (2013).

1.3 METHODS FOR PERFORMANCE ASSESSMENT OF BIOFUEL PRODUCTION SYSTEMS

The most commonly used methods to assess the viability of future biofuel production concepts are Techno-Economic Assessment and Life Cycle Analysis (see Figure 1-3). The figure provides an overview of the main steps included in the economic and environmental assessment of large future biorefinery concepts, including how relevant input is generated for Techno-Economic Assessment (TEA) as well as Life Cycle Assessment (LCA) of these concepts. The need for prospective assessment methods is implicit in the figure. This is due to lack of detailed data about future technologies, and lack of data about the surrounding systems in which these technologies may operate.

Techno-Economic Assessment (TEA) is often used in chemical process design in order to find the economic optimum subject to physical constraints (heat and material balances, thermodynamic limitations and maximum allowable emissions). Costs associated with compliance with environmental legislation can be included in the objective function. However, life cycle principles are often incorporated retrospectively, resulting in incremental environmental impact improvement rather than fuel production routes that minimize impacts across the full life cycle of the product. In the context of biorefineries, TEA generally refer to evaluations of the technical and economic performance and feasibility of production concepts for novel bioproducts. TEA may also provide input to comparisons of key performance indicators of different types of biorefinery systems.

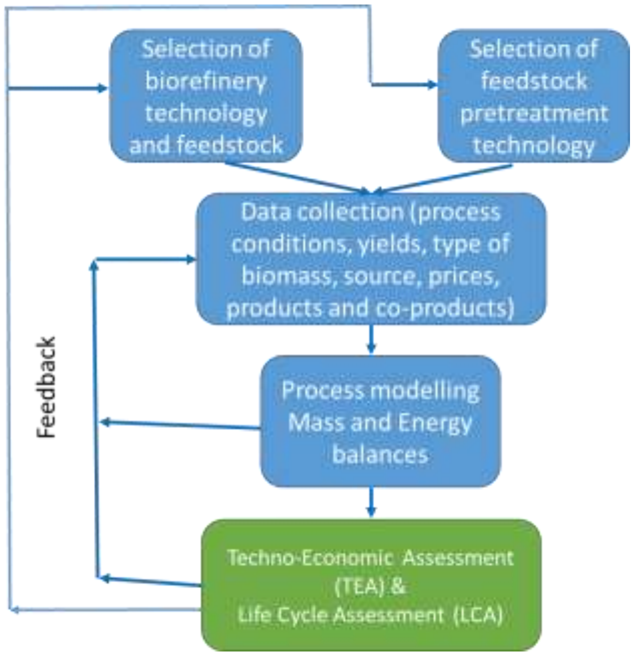

Figure 1-3 Overview of main steps in the economic and environmental evaluation of large future biorefinery concepts.

Life Cycle Analysis (LCA) is an environmental systems analysis tool that aims at determining the environmental impact of a product or service over its life cycle, from the extraction of raw material (cradle) to the end of life the of the product or service (grave). The procedure to carry out an LCA consists of four steps: goal and scope definition, inventory analysis (LCI), life cycle impact analysis (LCIA) and interpretation (Figure 1-4). The goal and scope define in detail the subject of the assessment and how the assessment is done; during the inventory analysis data related to resources needed and emissions (environmental loads) are gathered; these environmental loads are "translated" into environmental impacts during the LCIA; and finally, the results are interpreted and conclusions are drawn.

In addition to techno-economic and life cycle analysis tools, the design of sustainable biofuel supply chains requires joint consideration of economic, environmental, and social factors that span multiple spatial and temporal scales. A recent review paper by Zaimes et al. (2015) discusses key research opportunities and challenges in the design of emerging biofuel supply chains and provides a high-level overview of the current state-of-the-art in environmental sustainability assessment of biofuel production. The paper suggests that a modular multi-scale, multi-objective, supply chain optimization framework is required to design sustainable biofuel production processes and supply chains, as shown in Figure 1-5. Although the development of such an all-encompassing framework is obviously highly desirable and scientifically challenging, it can be argued that it is difficult, or even impossible, to achieve excellence in all stages of the framework. Furthermore, quantifying and assessing the economy-wide impacts as well as the ecosystem impacts of novel biofuel production concepts must take into account that conditions in the surrounding energy system will change, sometimes dramatically, over time. This increases the level of challenge associated with such assessments. Most research groups usually aim at achieving excellence at one scale, and attempts to cover several levels usually require strategic collaboration with other research groups.

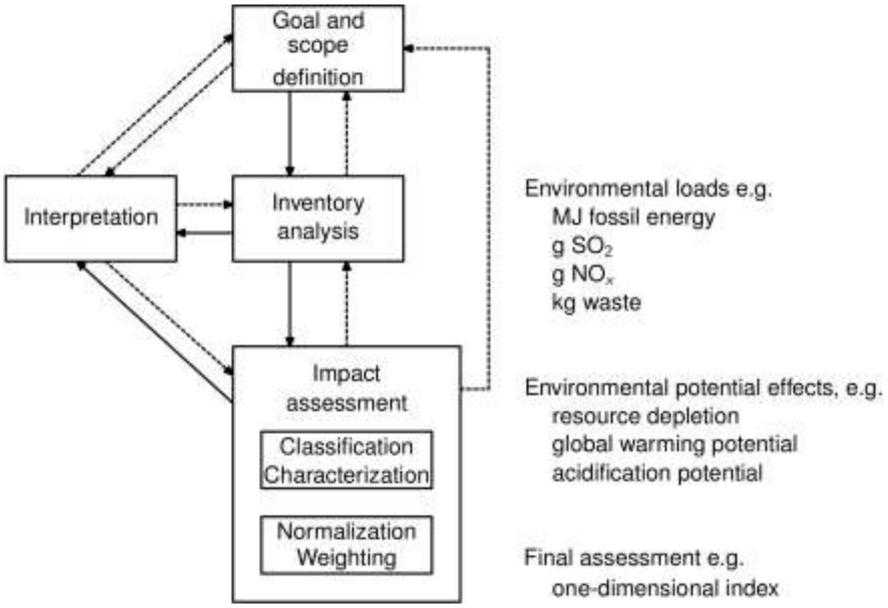

Figure 1-4. Life cycle assessment (LCA) framework.

1.4 AIM AND OBJECTIVES OF THIS WORK

Contributing to the development of a full-fledged tool for design and analysis of innovative biofuel production processes and supply chains is beyond the scope of this project. Instead, this work focuses on the methodological choices and assumptions made when applying TEA and LCA and other methods and tools to assessing biofuel production processes, according to the system boundaries depicted in Figure 1-6. The main focus is on how methodological choices and assumptions can lead to substantially different results, sometimes conflicting and difficult to interpret. This in turn leads to at least two, partly opposite problems: 1) assessments made using questionable assumptions or inadequate methods may yield misleading results and cause resources to be spent on developing production routes that are not sustainable in the long-term; and 2) conflicting and vague results may lead to uncertainty and paralysis – i.e. strategic investments are postponed until better data are available. Another key problem is that many long-term assessment studies avoid the issue of uncertainty by assessing future biofuel production technology assuming current conditions for the surrounding system. These problems together constitute a major challenge for industrial investors as well as policy-makers, and underlines the need for research efforts focused on ex-ante evaluation of the sustainability of future biofuel production processes and supply chains. One way in which this can be achieved is by using future scenarios for the surrounding system in order to identify robust alternatives for strategic decision support. Such an approach allows the system boundary usually adopted for TEA to be expanded to a more societal level.

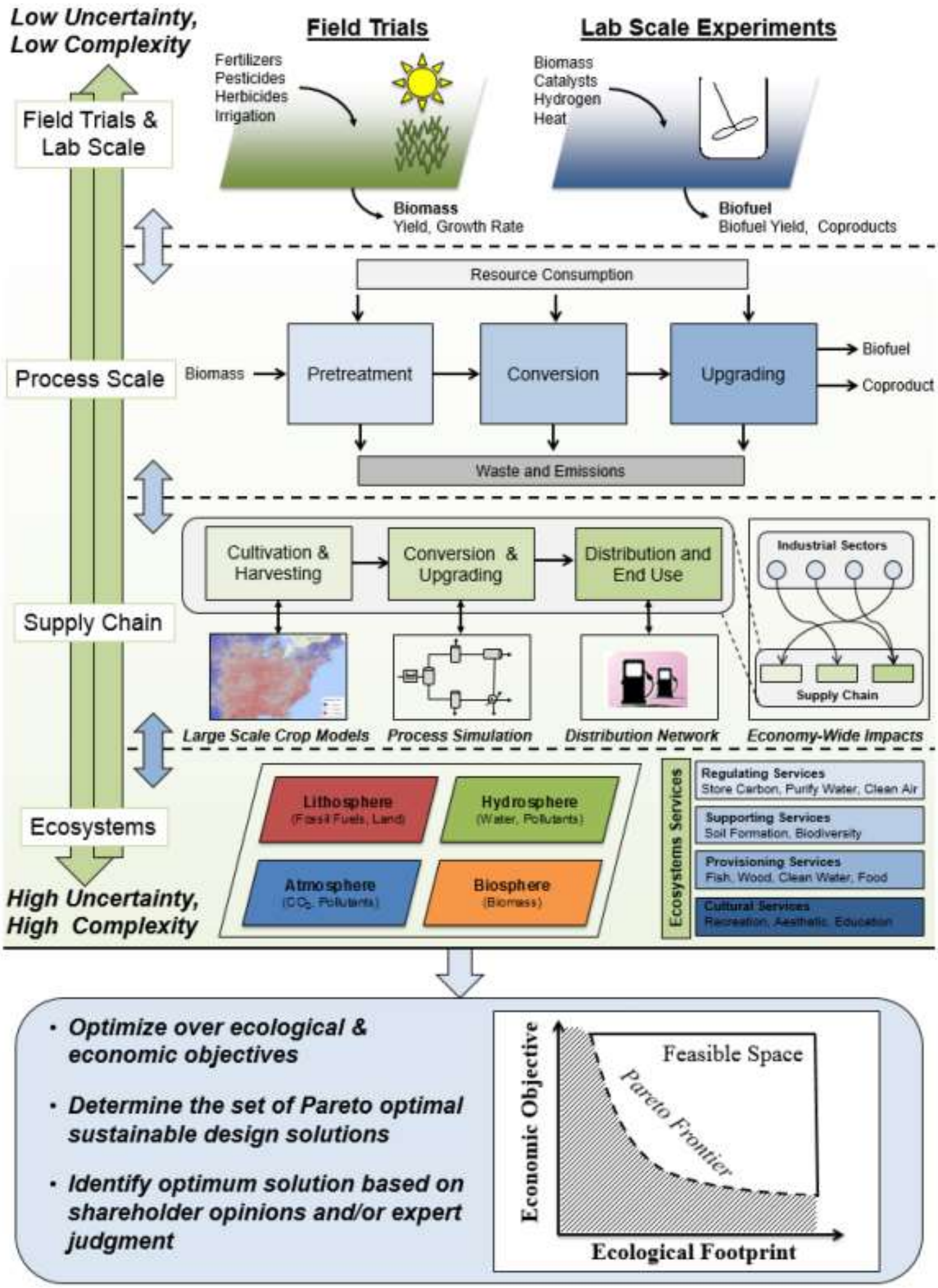

Figure 1-5 Overview of a Modular Multi-scale, Multi-objective, Biofuel Supply Chain Optimization Framework. Source: Zaimes et al (2015).

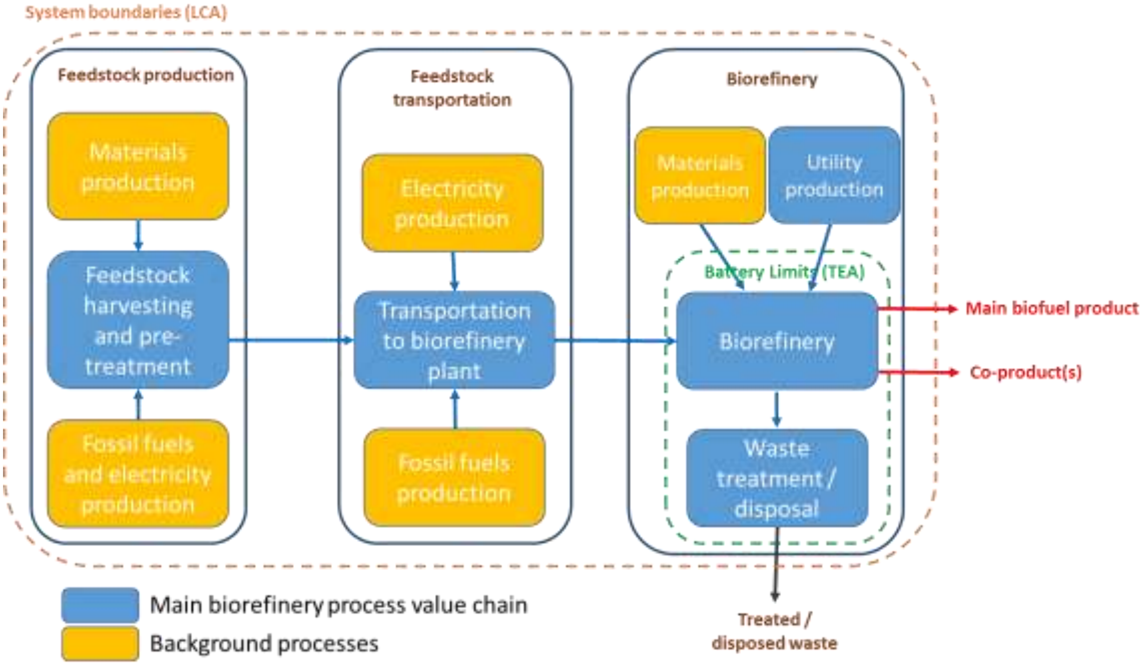

Figure 1-6 System boundaries for TEA and LCA studies of biorefinery process value chains.

To better understand the climate impact of new bio-based development routes at an early stage – so called *ex-ante* evaluation – it is important to be able to develop decision support tools for industry and politicians as well as to conduct early feasibility assessments. The results gained by this type of systematic assessment are also important as input to the developers of new technologies since environmental impact "hot spots" can be identified at an early stage and flawed production concepts can be discarded. Systematic ex-ante assessment also enables structured cooperation between technology researchers and systems researchers, as in the Skogskemi project (see Joelsson et. al (2015)) in which the potential for large-scale production of green commodity chemicals from forestry residues was assessed for three possible value-chains.

The overall aim of this work is to: (a) present a synthesis of current knowledge about methodology and principles for assessment of the long-term sustainability of new biofuel production routes with specific focus on carbon footprint; (b) provide a basis for strengthening Swedish expertise in this area through increasing cooperation between the leading Swedish academic organisations involved in this project; and (c) identify best-practices as well as important methodological gaps in previous work.

The specific objectives for the work summarized in this report include the following:

- Show the importance of a long-term approach for assessing both the economic and climate consequences of possible future changes in surrounding system conditions with respect to implementation of biofuel production concepts.
- Compilation of a state-of-the-art report on methods and approaches for assessing new biofuel production concepts in a long-term perspective.
- Describe and compare approaches being used today in the research groups participating in the project.

- Compile a collection of case studies, based on earlier work in the participating groups, quantifying the possible magnitudes of differences in results regarding economic performance and carbon footprint of future biofuel production processes, depending on differences in assumptions regarding conditions in the surrounding system.
- Discuss and compare the different approaches and identify how different approaches can complement each other.

1.5 REPORT STRUCTURE

Chapters 2-5 address four different key aspects of assessment approaches for biofuel production systems, and illustrate these aspects by presenting summaries of previous work conducted in the participating groups. Chapter 2 describes methods for Techno-economic Analysis (TEA). The Division of Energy Science at Luleå University of Technology conducts state-of-the-art research in this area, hence Chapter 2 describes methods and tools developed and used by this group and how these methods relate to the research front. Chapters 3 and 4 explore different aspects of Life Cycle Analysis (LCA) of biofuel production systems, as developed and used by the Division of Environmental and Energy Systems Studies at Lund University and the Division of Environmental Systems Analysis at Chalmers. Chapter 5 describes the energy market scenarios developed by the Industrial Energy Systems Analysis group at Chalmers for assessing the long-term economic and carbon footprint performance of biofuel productions, and how these scenarios can be used in TEA and LCA studies.

Chapter 6 presents new results for the METDRIV study conducted previously (see Börjesson et al, 2016) regarding the energy, greenhouse gas emissions (GHG) and cost performance of existing and potential new methane-based vehicle systems solutions. The input data used in the METDRIV study were based on average prices/costs and GHG emission factors valid at the time of the study for the surrounding supply systems. Chapter 6 illustrates how the results change if new input data based on results generated by the ENPAC (Energy Price and Carbon Balance Scenarios) tool developed at Chalmers are used instead.

Chapter 7 presents conclusions and suggestions for possible future work.

2 TECHNO-ECONOMIC ASSESSMENT OF INTEGRATED BIOREFINERIES

2.1 INTRODUCTION

In the context of biorefineries, Techno-Economic Assessment (TEA) generally refers to evaluations of the technical and economic performance and feasibility of production concepts for novel bio-products. TEA may also provide input to comparisons of key performance indicators of different types of biorefinery systems. The Division for Energy Science at Luleå University of Technology is one of the leading Swedish research groups in the field of development and application of TEA methods and tools applied to biofuel production concepts. This Chapter therefore presents a review of their activities which can be assumed to constitute a good description of state-of-the-art in this field.

A common procedure when performing TEA studies of biofuel production systems is to (i) model the system in a simulation tool such as Aspen Plus or use spread-sheet or mathematical programming software (e.g. Matlab or GAMS) to model and obtain resulting energy and material balances of the process, for a variety of different conditions (cases); (ii) evaluate the technical performance using the balances to calculate appropriate efficiencies; (iii) if the plant is a stand-alone unit, use the balances directly to size the process units and thereafter estimate the total project investment and operating costs. If the process is industrially integrated, the material and energy balances are translated to linear equations and supplied as inputs to Process Integration (PI) models. The PI model can be used to calculate resulting overall energy and resource efficiencies of the industry. The model can also be used for overall system optimization and to make sure that sub-optimization is avoided. An iterative modelling approach between process models and the PI models is normally used to ensure that all boundary conditions and constraints are met. The resulting balances are used to calculate overall efficiencies (including in some cases the impact on energy flows between the biorefinery plant and the background energy system) and to find the total project investment and operating costs.

The PI models used by the Division of Energy Science are commonly based on mixed integer linear programming (MILP) using the Java based software reMIND, GAMS or MATLAB in combination with Simulink. The reMIND model structure adopts a network of nodes and branches to represent a given process via MILP. The method was developed by Linköping University for modelling of industrial energy systems (Karlsson, 2011). reMIND has been used to analyze a wide range of various industries, such as the mining/steel industry (Larsson, 2004), foundry industries (Solding et al., 2009; Thollander et al., 2009), pulp mills (Ji et al. 2012; Klugman et al. 2009; Wetterlund et al. 2010), as well as district heating networks (Vesterlund & Dahl 2015; Wetterlund & Söderström 2010). MATLAB combined with Simulink has been applied in sawmills (Mesfun et al. 2016) and district heating networks (Vesterlund et al, 2017). Additionally, recent studies have used a generic state-of-the-art pulp mill, described in detail by Berglin et al (2011), to study concepts for integration of biorefinery concepts based biomass gasification technology (Carvalho et al, 2017).

Typically, the process models are based upon experimental data. Such data alone are, however, often insufficient since the biorefinery processes are interconnected in a commercial setting (i.e. industrially integrated). Additionally, the scale of an experiment may not reveal issues that may emerge at larger plant scales. TEA therefore also requires other types of data (scale factors etc) and can thereby aid in solving this scale-dependent problem and provides quantitative estimates that take scaling issues into account.

2.2 TECHNICAL PERFORMANCE ANALYSIS METHODS

Andersson et al (2013) summarizes four main methods used for calculating overall energy efficiencies of biorefinery concepts: (i) using mixed sources of energy carriers based on the first law of thermodynamics; (ii) by the use of electricity equivalents; (iii) by converting the mass and energy flows to their biomass equivalents (except the main product) or (iv) describing the mass and energy flows in terms of exergy.

Only using mixed sources of energy carriers as outputs over inputs to evaluate system performance can lead to an inadequate assessment of biofuel production systems, especially when low quality energy flows are considered on the same basis as high quality energy flows. Re-computing the energy carrier flows to electricity equivalents is often used as a simple approach to better value the diverse level of exergy of different streams (biomass, bark, hot water, steam, chemicals, etc.). All energy carriers (final product, biomass, etc) are converted to electricity equivalents according to efficiencies (η) based on best available technologies, shown in Table 2-1.

Table 2-1 Electricity generation efficiencies used for calculation of electricity equivalents. Source: Tunå *et al*. 2012; Andersson, 2016.

Energy carrier	η
Biomass	46.2%
Pyrolysis liquid	50%
Methanol	55.9%
District heating	10.0%
LP steam 4.5 bar(a) 150°C	16.6%
MP Steam 11 bar(a) 200°C	19.6%
IP Steam 26 bar(a) 275°C	22.6%
HP steam 81 bar(a) 490°C	27.2%

It should however also be mentioned that comparing system efficiencies of different production systems may be problematic and sometimes highly misleading. One reason is that different studies use different system boundaries for efficiency calculations. But even if the comparisons are made on equalized basis, it may be difficult. This is due to how the efficiency is defined and calculated and resulting efficiency differences or improvements are often in direct correlation with how the industries exploited their resources prior to the integration. The resulting efficiencies are therefore very site-dependent (Andersson, 2016).

2.3 ECONOMIC ANALYSIS METHODS

The economic analyses are based on the resulting energy and material balances from the modeling and include some form of profitability analysis under prevailing or future market conditions. The time perspective is generally chosen depending on the maturity of the technology.

Economic analysis can be used to estimate the net present value (NPV) and internal rate of return (IRR), based on the capital investment, as well as on the variable and fixed operating costs of the biorefinery. The discount rate needs to be chosen as well as the construction period (normally assumed to be 3 years). During the first year, the expenses are the engineering, construction and contingency costs. 80% of the total capital investment is normally assumed to be incurred during the second year and the investment is completed in the third year. The biorefinery is usually assumed to operate at 75% of full capacity in the third year, and at full capacity for the rest of the plant's technical lifetime. One month per year of downtime is assumed for plant maintenance.

The total capital investments are calculated by determining equipment costs based on literature data and real tenders. LTU has a unique in-house database for investment costs, in particular for biomass gasification plants and downstream equipment. If necessary, equipment costs are scaled as a function of capacity using the standard power law

$$C=C_{ref}\,(S/S_{ref})^{n}$$

where C and S correspond to the investment cost and the production capacity of each unit, respectively. The subscript *ref* denotes the investment cost and size of the reference units. The scaling factor *n* varies depending on type of equipment and is generally available in the literature.

The investment costs must usually be updated using the Chemical Engineering Plant Cost Index (CEPCI) to compensate for general price changes over time. It is however not recommended to use CEPCI over a time period exceeding five years, due to uncertainties in value appreciation and surrounding world factors (Andersson *et al*, 2013).

Prospective economic assessments of future biorefinery concepts involve great uncertainties. The technology readiness level (TRL) may be very low and experiments only carried out in lab-scale. No commercial supplier may yet exist, which means that no tenders are available and investment figures can be impossible to find. In this case, calculating the investment opportunities (IO) may be a more suitable method to compare different concepts or process configurations, see e.g. Heyne and Harvey (2013); Wetterlund et al (2010a). The annual IO is the difference between the operational costs including costs for feedstock, electricity etc. and the revenues from sold products including green electricity certificates when applicable. A prospective approach is obviously necessary for conducting such assessments. IO is used to characterize a system's potential to be economically viable and defined as the annual capital cost per unit of produced fuel for which the process achieves economic break-even. Future energy market scenarios can be used to estimate the economic value of energy flows, feedstock, etc.

Another prospective approach to manage uncertainties is to conduct sensitivity analysis by varying different parameters independently of each other, in order to evaluate their impact on the techno-economic performance.

2.4 ENVIRONMENTAL CONSIDERATIONS

Environmental performance assessment is beyond the scope of TEA. However, carbon footprint balances can be easily performed using the same energy and mass balances required as input for TEA studies. For example, fossil CO_2 emissions can, when suitable, be assessed in an expanded system, following the principles of consequential life cycle assessment (see e.g. Wetterlund et al 2010b, Zetterholm et al 2017). The approach is similar to that adopted at Chalmers discussed in Chapter 5. Biomass feedstocks are generally considered as limited resources and an increased demand for biomass due to changes in a production plant is assumed to lead to an increased use of fossil fuels elsewhere in the expanded system. The CO_2 effects of the increased biomass use are taken into account by assuming a reference biomass usage, for example co-firing with coal in power plants. Correspondingly, during evaluations of the primary energy use of a system, local as well as global fuel usage are considered. For example, the electricity produced or consumed in a studied biorefinery system is assumed to influence the surrounding electricity system. Thus the change in global fuel use due to an altered electricity balance is influenced by the efficiency of the electricity production of the surrounding system.

2.5 SPATIAL MODELING

Techno-economic analysis can also be used to identify cost-efficient localizations of biorefinery facilities in regions or countries. The BeWhere model (Leduc, 2009) has been developed in a partnership between the International Institute for Applied Systems Analysis (IIASA) and the Division of Energy Sciences in Luleå, and has been used in a number of regional, national and European studies. The Swedish model, BeWhere Sweden, was developed for bioenergy facilities in Sweden, and particularly for analyses regarding integration in existing energy industrial infrastructures and systems (Wetterlund et al., 2013). The strength of the model is that it considers geographical aspects related to the supply and demand of woody biomass from different sectors (e.g., site-specific integration possibilities, transportation distance, quantities etc.), as well as external factors (e.g., policy instruments and market conditions). BeWhere Sweden includes existing industrial sites (district heating systems, mechanical paper- and pulp mills, chemical pulp mills, saw mills and oil refineries) as potential locations for advanced biofuel production, with a number of site-specific conditions being explicitly considered. Multiple possible production routes, biomass feedstocks and biofuels are included in the model. Furthermore, plausible biofuel scenarios including energy market prices, policy instruments, capital investments, feedstock competition, biofuel demand and integration possibilities with existing energy system are used in the evaluations.

BeWhere Sweden is a valuable tool for simulation and analysis of the Swedish energy system, including the industry and transport sectors. Governmental agencies often base their analyses on results from the MARKAL and EMEC models, however none of these consider the spatial distribution of feedstock, facilities and energy demands. Sweden is a widespread country with long transport distances and where logistics and localization of production plants are crucial for the overall efficiency. BeWhere Sweden considers this and may thus contribute with valuable input for different biofuel production stakeholders as well as for government and policy makers. The BeWhere Sweden model can under different future scenarios, be used to estimate

- The most cost effective and robust biofuel production plant locations
- Required investments and costs to reach certain targets and demands

The model minimizes the cost of the entire studied system. The system cost includes costs for feedstocks, transportation and distribution costs (feedstock and final products), set-up, operation and maintenance costs for new production plants, costs for imported feedstocks and final products, revenues for co-produced energy carriers, costs of fossil energy used in the system, and costs and revenues related to various policy instruments. In addition to this, the impact of fossil CO_2 emissions can be internalized in the model, by adding a cost on the supply chain CO_2 emissions (including off-set emissions from displaced fossil energy, following the principles of system expansion described in the Environmental Considerations section (see Wetterlund et al., 2013). The results can be used to identify and analyze possible policy target conflicts, for example how increased forest protection areas may contradict targets regarding biofuel production shares. It may further be used to analyze different proposed policy instruments.

3 INTERDISCIPLINARY SYSTEMS STUDIES OF BIO-FUELS FROM A LIFE CYCLE PERSPECTIVE

3.1 INTRODUCTION

The Division of Environmental and Energy Systems Studies (EESS) conducts is a major and internationally acclaimed group in this field of research. Life cycle assessment (LCA) is the main tool used, often in combination with additional analyses to cover other aspects such as costs, land use, policy implications, etc. The selection of methodological approach and tools normally proceeds from the research question to be addressed, which may include one or several scientific fields. This Chapter includes elected examples that illustrate research approach adopted.

3.2 LCA AND DIFFERENT PERSPECTIVES

The LCA studies conducted at EESS put significant emphasis on highlighting how the results may vary due to different methodological approaches. For example, Figure 3-1 shows how the GHG performance of different biofuels varies due to different allocation methods, system boundaries and reference land use (Börjesson and Tufvesson, 2011). LCAs may be divided between attributional LCA (ALCA), reflecting the actual situation, and consequential LCA (CLCA), showing the consequences of a changed situation. These different approaches are central to most LCA practitioners, including the Environmental Systems Analysis group at Chalmers (see Chapter **Fel! Hittar inte referenskälla.**). A hybrid LCA approach is often adopted by EESS in order to cover both perspectives including both allocation and system expansion, average and marginal input data, etc (Olofsson et al, 2017; Soam et al, 2017; Börjesson et al, 2015; Lantz and Börjesson, 2014; Börjesson et al, 2012). The results presented can thus be useful under different situations covering a variety of research questions and practical applications. Other examples include studies to develop attributional LCA into a consequential framework by building scenarios, including both average and marginal data (see e.g. Yang, 2016). The well-to-wheel studies performed by JRC et al (2014) also adopts a hybrid approach when calculating the GHG and energy efficiency performance of vehicle fuels.

3.3 USE OF LCA TO PROVIDE DATA FOR SETTING POLICY INSTRUMENT LEVELS

LCA became a sharp policy tool when a standard for calculating the GHG performance of biofuels was introduced in the EU's Renewable Energy Directive (RED) that was implemented in 2009 (European Commission, 2009). RED adopts an allocation approach based on the lower heating value of the products and the assumption that residues used as feedstock have zero upstream emissions. The main motivation for these simplifications was to propose a calculation procedure that can be used by economic operators. A The major drawback is, however, that such simplifications may not lead to the promotion of the most optimal biofuel production systems from a broader GHG emissions perspective.

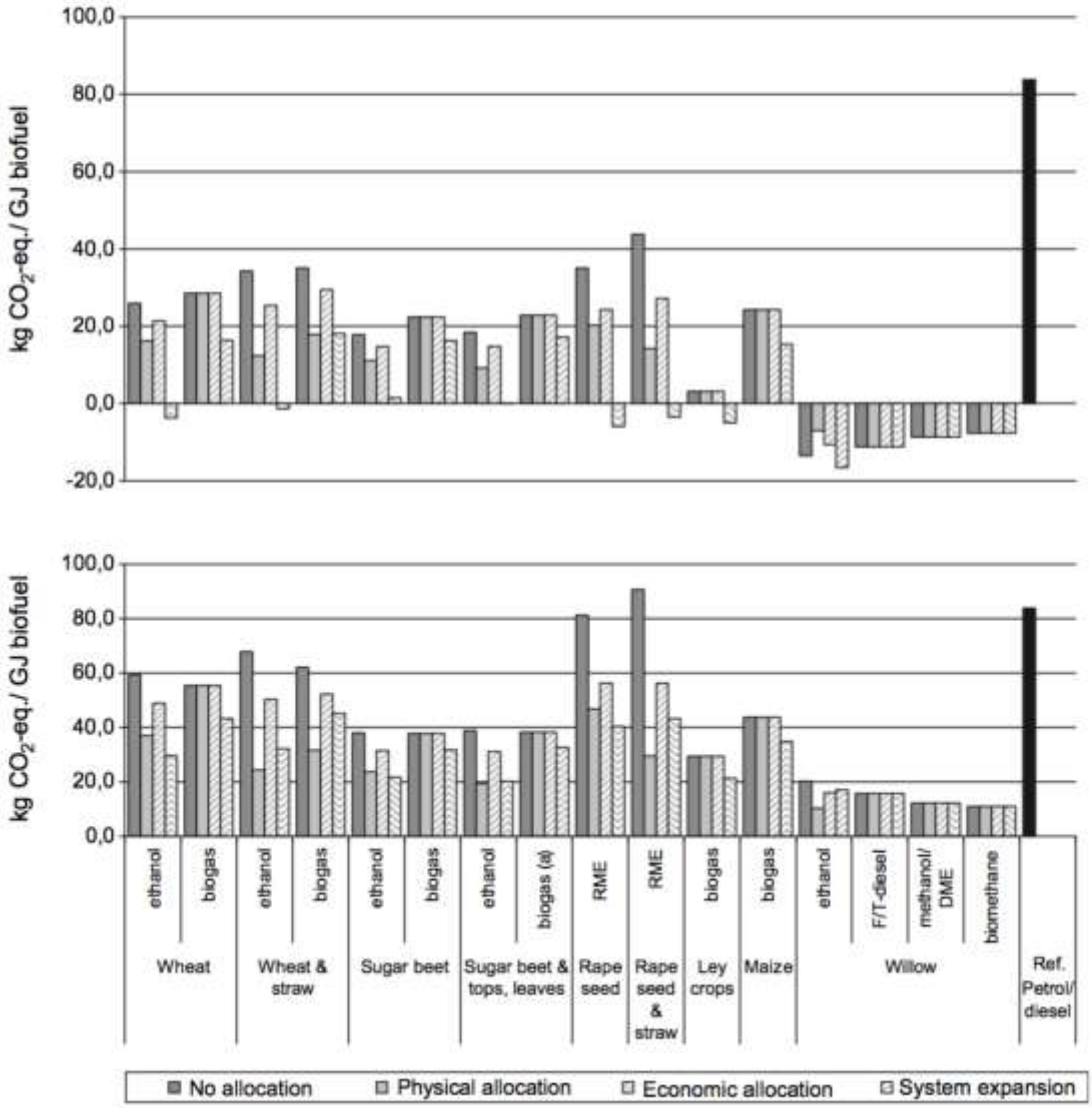

Figure 3-1 Contribution to global warming potential, expressed as kg CO_2-equivalents per GJ biofuel, including different allocation methods and system expansion. The alternative land use reference system is wheat cultivation (above) and unfertilised grass (below).

Several environmental systems studies performed at EESS and elsewhere (e.g. Olofsson et al, 2017; Börjesson et al, 2015; Karlsson et al, 2014) compare the RED calculation methodology with the system expansion approach recommended by the ISO standard for LCA studies (ISO, 2006). Figure 3-2 illustrates the GHG performance of biogas production using various feedstock residues and by-products and calculation methodologies (Tufvesson et al, 2013). In the RED calculation, current uses of residues as feedstock for alternative products (often protein feed) are not taken into account. In the system expansion approach, the alternative production of protein from dedicated feed crops is included showing the net GHG performance. The rapeseed cake feedstock is classified as a by-product in RED, thus upstream GHG emissions are included.

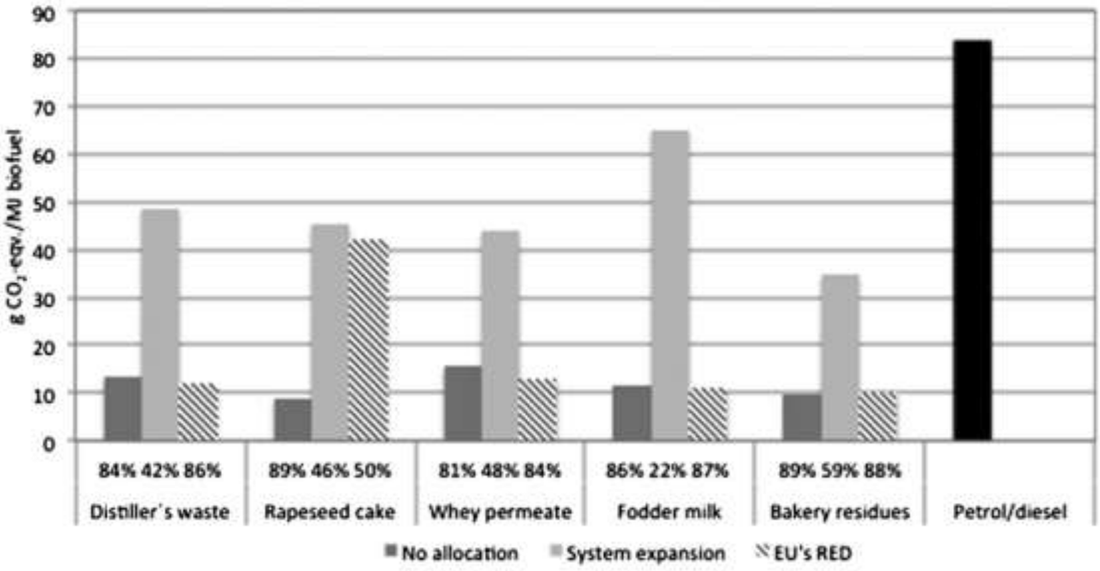

Figure 3-2. Contribution to global warming potential per MJ biogas for the different substrates, applying the calculation methodology in EU's RED without allocation and system expansion. The reduction in GHG emissions compared with petrol and diesel is also shown (Tufvesson et al, 2013).

Another example of a comparison between the RED and ISO calculation methodology is shown in Figure 3-3, also including reduced soil carbon accumulation when logging residues are harvested and used as feedstock for biofuel production (Börjesson et al, 2013). In these cases, the ISO calculation methodology leads to higher GHG emissions than the RED methodology.

Coherency is a critical aspect when using input data regarding the primary production system and the alternative system included by the system expansion approach. If marginal data are used, this must be done for all the systems included. The same applies when average data are considered. For example, previous LCA's of ethanol production systems based on food crops sometimes mix marginal and average data in an inconsistent way. In some studies, marginal data regarding an expanded primary production of feedstock in form of corn, sugarcane or wheat are mixed with average data for production of protein feed crops replaced by the by-products generated in the ethanol production system (see e.g. Searchinger et al, 2009). This leads to inconsistent results since the main products and co-products are not handled in a comparable way. In the systems studies conducted at EESS, average input data are used consistently in base cases, also when the system expansion approach is applied. The main reason is that the nature of the by-products utilisation are known as well as the alternative products that are replaced for many existing commercial biofuel systems. Another reason is that the potential indirect consequences of the primary biofuel production systems are highly uncertain and difficult (impossible) to assess. Marginal data are therefore usually included in the uncertainty analysis and in a coherent way for all the products included. In addition, issues related to expanded land use are often covered in additional studies as complements to the LCAs.

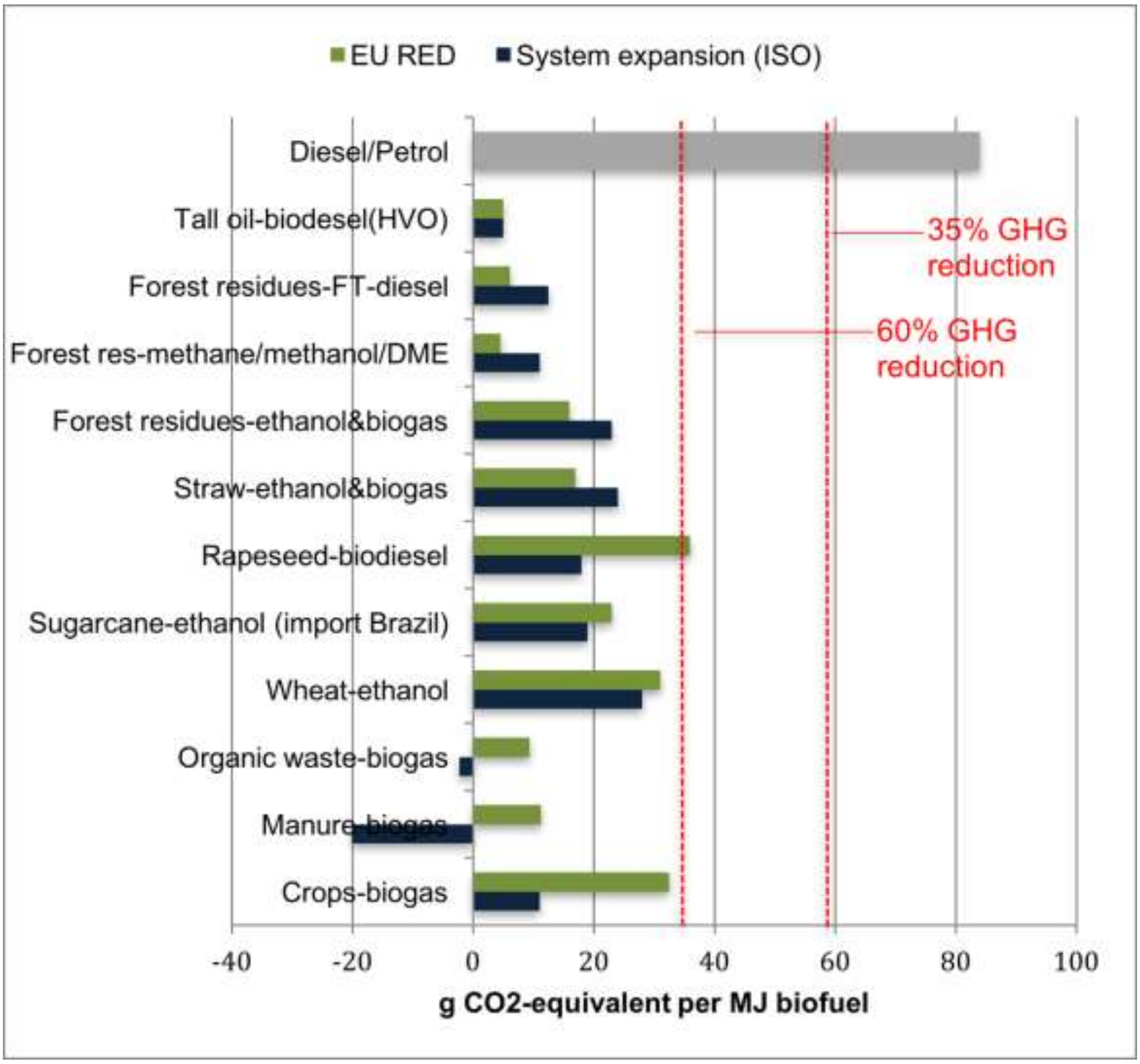

Figure 3-3. Contribution to global warming potential per MJ biofuel when the calculation methodology in EU's RED and the system expansion approach are applied. The reduction of GHG emissions compared with petrol and diesel is also shown (Börjesson et al, 2013).

The EESS group does not use any explicit LCA software modelling tools, such as SimaPro and Gabi, which are connected to LCI databases such as Ecoinvent. Instead the group has built up dedicated in-house calculation models in Excel and in-house LCI databases for the biofuel systems studied, based on actual literature data, contacts with key actors etc. Full control of calculations and associated data is thereby achieved so as to ensure transparency. However, the LCA studies conducted in this manner are often less complete regarding all the details in the supply systems compared with, for example, SimaPro calculations based on Ecoinvent data. However, such an approach enables the work to focus on identifying the most relevant parameters and processes in the various biofuel production systems and secure high quality input data, from a technical, geographical and time perspective. The cut-off criteria are thus somewhat different than in standardized LCA software tools but still adjusted to make reliable, adequate and sufficiently complete LCAs. A potential risk of using existing LCI databases, such as Ecoinvent, is that the data quality sometimes may be questionable due to the age of the data, its geographical representation, technical relevance etc. Furthermore, for prospective assessment of emerging technologies and biofuel production systems, corresponding input data is usually not available in existing LCI databases. In these cases, results from simulations of large-scale commercial production systems generated using software tools such as Aspen Plus can be used instead. Here, lab-scale data are used as input but translated and adapted to represent large-scale production based on existing commercial technology. Results from Aspen Plus simulations include mass balances, energy inputs and outputs, conversion efficiencies etc., which are then converted into environmental performance in LCA studies.

3.4 COST CALCULATIONS

The approach adopted at EESS for calculating the production costs of biofuels normally includes investment costs, annual costs of capital and the annuity calculation method. For existing production technology, generic literature data in combination with data from economic operators are used. For prospective assessment of emerging technologies, estimation of future costs is normally based on data from external modelling studies, for example using tools such as Aspen Plus. Future potential changes in feedstock costs, energy prices, taxes and other policy incentives etc., are normally covered by simplified sensitivity analyses (see e.g. Lantz, 2012; Joelsson et al, 2015; Börjesson et al, 2016; Olofsson et al, 2017). Figure 3-4 illustrates results from cost calculations regarding biofuel production in Sweden under current conditions, both including commercial and emerging systems (Börjesson et al, 2013). The uncertainty interval reflects variations in feedstock costs during the last years, uncertainties in investment costs of emerging technologies etc.

The uncertainty intervals are normally +/- 30% (sometimes 50%) for investment and feedstock costs (Börjesson et al, 2016; 2013). Furthermore, different levels of discounting rate (e.g. 6%, 10% etc.) are also included in the sensitivity analyses. The costs are assumed to represent average costs of current and future commercial biofuel plants and systems, thus the costs are not considered as future marginal costs for feedstocks etc. However, in some situations, changes in future feedstock costs in the sensitivity analyses may correspond to future marginal costs estimated by others, but this is not specifically considered in the assessments.

3.5 DISCUSSION

The approach of systems studies of biofuels at EESS differ somewhat from systems studies performed at other universities in Sweden, such as Chalmers and Luleå University of Technology, since EESS does not make use of any explicit modelling tool. Different approaches and methods are used depending on the research question in focus. Future changes in the overall energy system, prices of energy carriers etc., are often addressed by additional sensitivity analyses. Important research questions at EESS are how specific biofuel systems can be designed to optimise the environmental performance, also taking into account local conditions, but also how well current assessment methods and methodological choices reflect the “actual” performance of the specific biofuel system from a broader perspective.

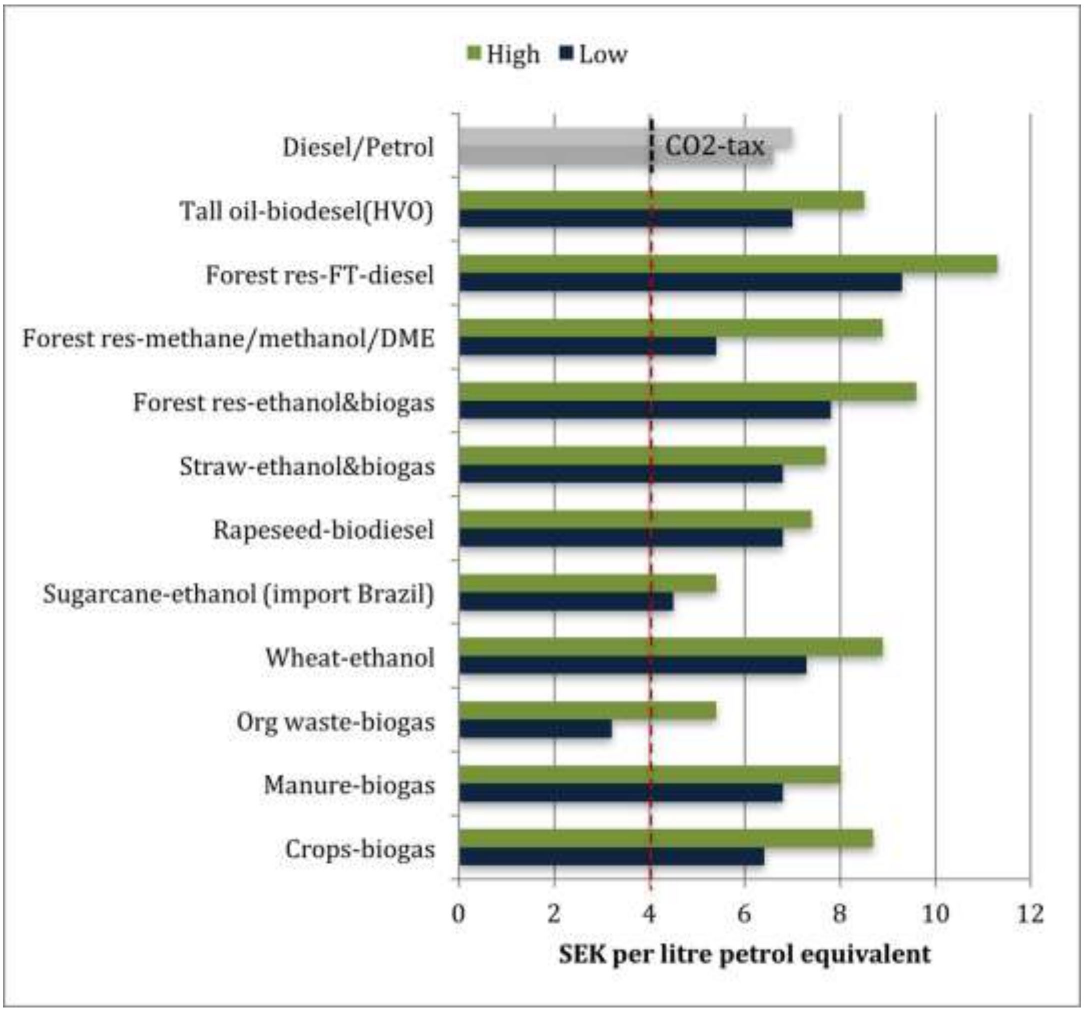

Figure 3-4. Estimated production cost of various biofuels under current Swedish conditions, expressed as SEK per litre petrol equivalent, including an uncertainty interval reflecting variations in feedstock costs, uncertainties in investment costs etc (Börjesson et al, 2013).

4 PROSPECTIVE LIFE CYCLE ASSESSMENT OF BIO-FUELS

4.1 INTRODUCTION

Over the years, a large body of work has been built up that uses LCA to determine the environmental sustainability of biofuels (and other forms of bioenergy). Since climate change has been and continues to be a significant driver for the development and production of biofuels, determining greenhouse gas (GHG) emissions and their impact on global warming has been one of the focal points of LCA studies of biofuels (Cherubini and Strømman 2011). However, determining the impacts due to land use (land occupation) and land use change (land transformation) of biofuels production and use, such as impact on biodiversity (see e.g. Lindqvist et al. (2016)) and climate (see e.g. Searchinger et al. 2008), have generated a lot of discussion about methodological aspects to determine the environmental benefits of biofuels. A guideline for the assessment of land use impacts has been developed by UNEP/SETAC (Koellner et al. 2013), but relatively few case studies have been carried out using this guideline to demonstrate its robustness.

Methods to account for the impacts of biogenic carbon emissions (i.e. carbon emissions from a renewable source, mostly in the form of biogenic CO_2) have been developed by e.g. Cherubini et al. (2011) and Pingoud et al. (2012). A consensus about these methods has not yet been reached (Liptow et al. 2018). Despite these methodological issues, LCA is considered to be a powerful tool to determine the environmental impacts of biofuels production and use.

One of the main general discussions in the LCA community is the choice of attributional vs. consequential LCA, as discussed in detail in the previous Chapter. This discussion is also relevant for LCA of biofuels, especially when considering indirect effects of biofuel production such as land transformation (direct and indirect land use change (dLUC and iLUC, respectively)). Such effects can be considered in a consequential LCA since the analysis method is change-oriented. Attributional LCA aims at accounting for all environmental impacts of a system and does not focus on changes due to a decision that is made, and thus cannot be used to account for these effects.

4.2 PROSPECTIVE LCA

LCA can also be applied in a prospective (or *ex ante*) setting, i.e. the methodological choices made to carry out the LCA reflect the future nature of the technology being assessed. Methodology development for this type of LCA is one of the areas of expertise of the Environmental Systems Analysis (ESA) group at Chalmers, and the work of this group is the point of departure for the remainder of the Chapter.

Prospective LCA is clearly relevant if the technology is at the early development stage. Furthermore, LCAs are increasingly performed as part of technology development projects (see e.g. Xiros et al. (2017)). The goals of such LCAs are to determine the environmental impacts of the technology (how does it compare to current technology?), and to determine its environmental hotspots (how can the technology be improved from a life cycle environmental point of view?). The results can help guide technology developers, researchers and industry decision makers towards an environmentally benign technology or product.

The definition of temporal boundaries of a prospective assessment is essential. Prospective assessments are set at a certain point in the future, and this needs to be reflected in the assessment, both for the process or product under study (foreground system) itself and the surrounding processes (background system) with which the former interacts. A recent paper (Arvidsson et al. 2018), besides defining prospective LCA (pLCA), gives recommendations for doing prospective LCAs. It should be noted that prospective LCAs can both be attributional and consequential, however Arvidsson et al. (2018) focus on prospective attributional LCA. Such LCAs attempt to fully account for environmental impacts of an emerging technology at a certain point in the future, and do not focus on the consequences such a technology may have on the surrounding systems. The current discussion is however not about the differences between attributional and consequential LCA, and the reader is referred elsewhere (Brandão et al. 2014, Dale and Kim 2014, Plevin et al. 2014, Suh and Yang 2014, Zamagni et al. 2012). pLCA is defined by Arvidsson et al. (2018) as "studies of emerging technologies in early development stages, when there are still opportunities to use environmental guidance for major alterations". Figure 4-1 shows the evolution of technology diffusion, knowledge about the technology and design freedom. In order to provide guidance to technology development, a prospective assessment should be done during the formative phase or early in the growth phase. The assessment should however be done for a time at which the technology has evolved to the saturation phase or late in the growth phase.

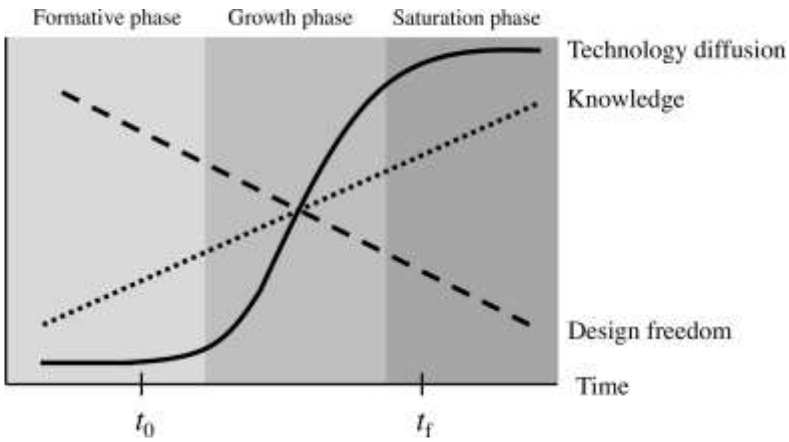

Figure 4-1. Curves representing technology diffusion, knowledge about the technology and design freedom. t_0 is the time when the assessment is done; t_f is a future time for which the assessment is done. Source: Arvidsson et al. (2018).

Arvidsson et al. (2018) focus on three main methodological choices relevant for pLCA:

1. technology alternatives to be modelled;
2. foreground system data including production scale; and
3. background system data.

Their recommendations are made based on a non-exhaustive review of prospective attributional LCA studies of a range of different technologies and products (not only including biofuels or other forms of bioenergy). The recommendations are related to the definition of the scope of the assessment. Closely related to these recommendations is the definition of the boundaries of the technical system under study, as illustrated for an industrial process system in Figure 4-2.

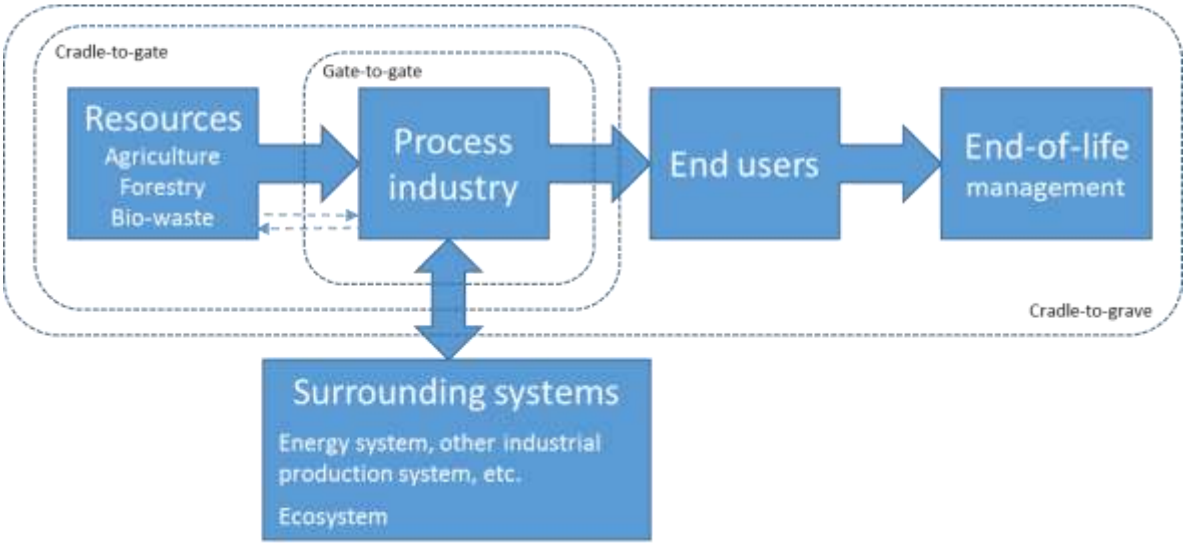

Figure 4-2. Industrial production system within the bio-based economy.

Is it sufficient to define the system as a production process by itself (indicated as “Process industry” in Figure 4-2), resulting in a so-called “gate-to-gate” system? Such a narrow system delimitation may be sufficient for the assessment of, e.g. heat integration projects in an existing industrial plant. Such assessments may, despite their limited scope, have a prospective character due to, e.g. the introduction of technology currently in development in a given production plant. Nevertheless, the outcomes of such projects often also have consequences for the upstream activities, such as the amount of renewable resources extracted. The system can thus be expanded to “cradle-to-gate” to include the extraction of the raw materials and their use in an industrial process (see Figure 4-2). Arvidsson et al. (2018) suggest two approaches for the choice of technology modelling:

1. focusing on one particular function that can be satisfied by a range of technologies. An example is the assessment of transportation technologies that are propelled by different fuels.
2. performing “cradle-to-gate” LCAs of production technologies that can be used as building blocks in future “cradle-to-grave” studies. An example is LCA of a technology under development for bioethanol production from wheat straw (Janssen et al. 2014) or wood chips (Janssen et al. 2016) which will most likely be used as a transportation fuel in the short term, but in the future may also serve as a building block chemical for e.g. bio-polyethylene production (Liptow et al. 2015).

Besides these two approaches discussed in Arvidsson et al. (2018), studying a specific technology to underline a relevant future consideration can also be considered as a modelling approach. In the case of the example of bioethanol as precursor for bio-ethylene, it can be used for the production of bio-polyethylene (bio-PE). Bio-PE may subsequently be used for the production of plastic grocery bags that eventually will end up in the waste management system where they may be recycled or incinerated. The technical system can thus be expanded to include the downstream activities (indicated by “End users” and “End-of- life management” in Figure 4-2). It should be noted that in the case of bio-PE, recycling networks exist, whereas in the case of other materials such recycling networks may not yet exist, and thus waste management scenarios may be an important part of a prospective assessment.

Arvidsson et al. (2018) also identify two main strategies for modelling future foreground production systems and scale (see Figure 4-3):

1. predictive scenarios that illustrate some likely development based on forecasts or trend analysis. Applying learning curves to predict future performance of a technology can be used to construct such scenarios. Another way to construct predictive scenarios is via the use of engineering-based scaling laws. Furthermore, current data can be applied to construct predictive scenarios when it is plausible that a system does not change within the time frame of the study.
2. scenario ranges including extreme scenarios. One example is the use of stoichiometric relations to model minimum impact scenarios. For heating processes, a low impact scenario can be modelled by assuming a very high efficiency. Similarly, a high impact scenario can be modelled by assuming a low heating efficiency.

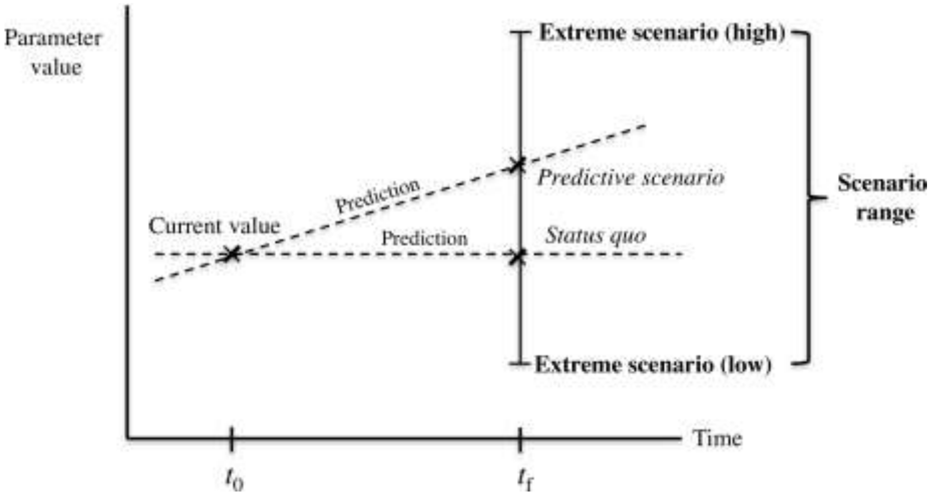

Figure 4-3. Different scenario types in prospective LCA as proposed by Arvidsson et al. (2018). t_0 is the time when the assessment is done; t_f is a future time for which the assessment is done.

Data sources for modelling foreground systems typically include scientific articles, patents, or lab results.

Lastly, Arvidsson et al. (2018) provide recommendations for the modelling of the background system:

1. apply a similar strategy as for the foreground systems, using predictive scenarios or scenario ranges. One example is to use predictive scenarios for the fossil energy mix in a country (Janssen et al. 2014).
2. omit the background system altogether when performing pLCA of a technology in development. The results of such studies can then be coupled to a specific background system depending on the goal of the study.

These strategies can be employed in order to avoid a mismatch between the foreground and background systems.

Spatial boundaries also need to be defined in prospective assessments, as discussed in Section 2.5. This is of particular importance for the potential origin of the biomass used, for the location of a production plant that uses this biomass, but also for the location of where a product is used and disposed of. These considerations stem from taking a product perspective. A landscape perspective offers an alternative view, and may, within the scope of an emerging bio-based economy, provide insight into how to sustainably manage and use the land that is to provide biomass for production systems (Börjesson et al. 2017). These two perspectives can be integrated, as implemented by Hammar et al. (2017), in order to determine the climate impact of willow energy by combining life cycle assessment with geographic information system mapping.

Defining the system boundaries strongly depends on the goal of the assessment. For example, if the goal of the assessment is to determine the environmental hotspots of or high cost centres for a technology under development, an attributional approach that fully accounts for all environmental impacts or costs can be sufficient (see e.g. Janssen et al. (2014), Janssen et al. (2016)). If the assessment's goal is to determine changes in environmental impacts or costs due to use of the technology in development, then a consequential approach is more likely to be appropriate. Typically, this includes an expansion of the system boundaries to account for these changes and what effect they may have on other systems. More detailed knowledge of the surrounding systems and their complexity may thus be required in a consequential approach. In the case of prospective assessments, an additional consideration is the uncertainty of what a production system will look like at an industrial scale, and what the surrounding systems will look like at a certain point in the future. Prospective assessments may therefore not be able to incorporate the required level of detail depending on the modelling approach that is taken, or this detail may not even be relevant for reaching the goal of the assessment. Rather, prospective assessments will provide guidance to stakeholders using scenario and sensitivity analyses to cover possible future situations for the system under study, as discussed in Chapter **Fel! Hittar inte referenskälla.**.

4.3 VARYING THE FUTURE BACKGROUND SYSTEM

One strategy that Arvidsson et al. (2018) mention for modelling future background systems is the use of predictive scenarios. In the LCAs of ethanol production from wheat straw and wood chips under high gravity conditions (Janssen et al. 2014, Janssen et al. 2016), scenarios for the share of fossil fuels in the future energy mixes in Denmark were constructed. This was done because these LCA studies found that a large share of the environmental impacts is caused by enzyme production and use. The production of these enzymes is situated in Denmark and uses a significant amount of fossil resources (Liptow et al. 2013). The constructed scenarios were based on studies by Lund and Mathiesen (2009) and the Danish Energy Agency (2011), and they predict the Danish energy mix in 2015 with a fossil share of 80%, in 2030 with a fossil fuel share of 67%), and 2050 with a fossil fuel share of 50%. Furthermore, the fossil fuel mix itself changes by largely phasing out coal use and replacing it with natural gas, while maintaining oil use. This analysis was done for three process configurations for the wheat straw- based and for the wood chips-based ethanol production (Figure 4-4 and Table 4-1, respectively).

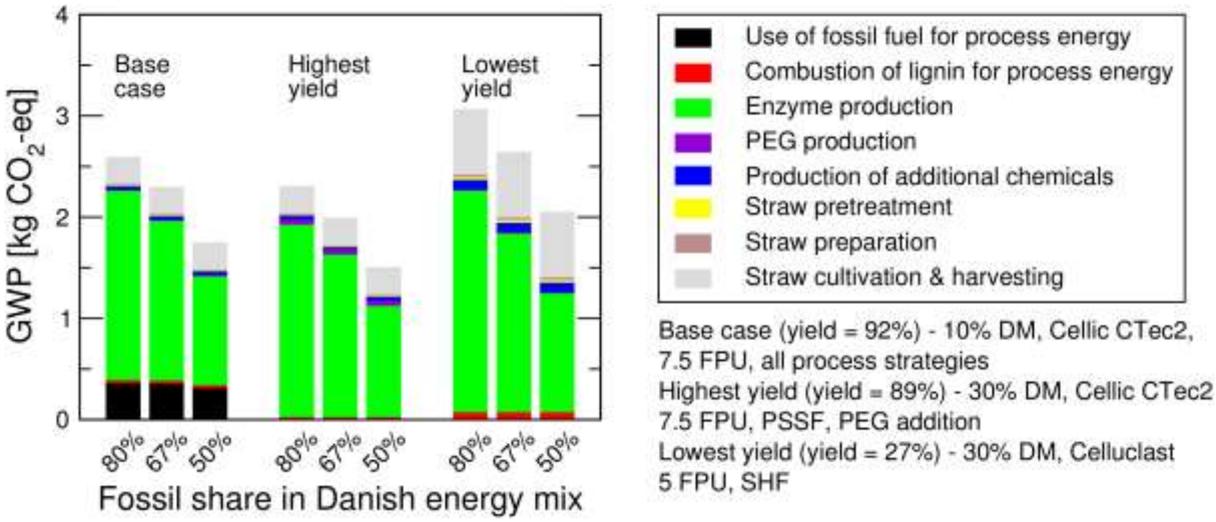

Figure 4-4. Global warming potentials (GWP) (in kg $CO_{2,eq}$ per liter of ethanol produced from wheat straw) due to projected changes in the Danish energy mix of the: a. base case (10% DM, 7.5 FPU, all process strategies, yield = 92%); b. high gravity process configuration with the highest yield (30% DM, PEG addition, Cellic CTec2, 7.5 FPU, PSSF, yield = 89%); c. high gravity process configuration with the lowest yield (30% DM, Celluclast, 5 FPU, SHF, yield = 27%).

The results show that, for both feedstocks, the total GWP of the configurations decreases by approx. 30% when the share of fossil energy is reduced from 80% to 50%. The contribution to GWP due to enzyme production decreases significantly (ca. 40%), as shown in Figure 4-4 for the wheat straw ethanol production. This result indicates that the environmental impact of the process configurations can be improved significantly by adopting a cleaner enzyme production. Combined with the results of analyses done for the foreground system (enzyme recycling and on-site (instead of off-site) production of enzyme), these results point out that by reducing enzyme use and by cleaner production of enzyme, either on- of off-site, a significantly decreased environmental impact of ethanol production under high gravity conditions can be achieved.

Table 4-1. Global warming potentials (GWP) (in kg $CO_{2,eq}$ per liter of ethanol produced from wood chips) due to projected changes in the Danish energy mix. This was done for the: a) base case (detoxification with Na2S2O4, PSSF at 12% DM and 30ºC); b) process configuration with the highest yield at 20% DM (washing of slurry, PSSF at 40ºC); and c) process configuration with the highest yield at 30% DM (adaptation of yeast + extra nutrients, SHF at 30ºC).

	Fossil share in energy mix		
	80% (2015)	67% (2030)	50% (2050)
Process configuration	GWP [kg $CO_{2,eq}$ per litre ethanol]		
a) Base case	3.4	3.0	2.4
b) Highest yield at 20% DM	2.7	2.4	1.9
c) Highest yield at 30% DM	3.1	2.7	2.1

5 ENERGY MARKET SCENARIOS FOR ASSESSMENT OF FUTURE INTEGRATED BIOFUEL PRODUCTION CONCEPTS

5.1 INTRODUCTION

This Chapter focuses on methods and tools developed by the Industrial Energy Systems Analysis (IESA) group at Chalmers. Profitability and net GHG emissions reduction potential of future advanced biofuel production concepts must be assessed by quantifying their impact within a future energy market context. Future energy market conditions are, however, subject to significant uncertainty. As discussed in Chapter **Fel! Hittar inte referenskälla.**, one way to handle decision-making subject to such uncertainty is to evaluate candidate investments using different scenarios that include future fuel prices, energy carrier prices, as well as indicative values of GHG emissions associated with important energy flows related to industrial plant operations. By assessing profitability for different cornerstones of energy market conditions, robust investment options can hopefully be identified, i.e. investment decisions that perform acceptably for a variety of different energy market scenarios.

5.2 SCENARIO TYPES AND THEIR USAGE

A user-oriented overview of scenario types and techniques and their usage in the vast field of future studies is presented in Börjesson et al (2006), who distinguish between three main categories of scenario studies: predictive (What will happen?); explorative (What if?); and normative (How can a certain objective be reached?). For each scenario category, the resolution is then increased by distinguishing two different scenario types.

Predictive scenarios regarding the background system can include forecast scenarios and what-if scenarios, as discussed in Section 4.2. Forecasts focus on what will happen on the condition that a likely development occurs. What-if scenarios focus on what will happen if a specific event occurs. Such scenarios are primarily drawn up to make it possible to plan and adapt to situations that are expected to occur. The annual OECD/IEA report World Energy Output (OECD/IEA, 2016a) is a well-established example of predictive scenarios in which medium to long-term energy projections using the World Energy Model (WEM) are presented. The New Policies Scenario takes into account the policies and measures that affect energy markets that had been adapted as of mid-2016, and typifies the What-if approach. The Current Policies Scenario is also a What-if scenario which considers only policies for which implementing measures had been formally adopted as of mid-2016 and makes the assumption that these policies persist unchanged. The WEM model is a large-scale simulation model designed to replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by-region projections for the World Energy Outlook (WEO) scenarios. Developed over many years, the model broadly consists of three main sections covering:

- final energy consumption including residential, services, agriculture, industry, transport and non-energy use
- energy transformation including power generation and heat, refinery and other transformation and
- fossil-fuel and bioenergy supply

Outputs from the model include energy flows by fuel, investment needs and costs, CO_2 emissions and end-user pricing and these outputs are calculated for each of the 25 regions modelled in the WEM. An extensive effort is undertaken each year to incorporate up-to-date energy and climate-related policies and measures into the modelling and analysis. The methodology and assumptions behind the World Energy Model are discussed in detail in (OECD/IEA, 2016b).

Normative scenarios can be used to address the question "How can a specific target be reached?" Preserving scenarios investigate how the target can be reached by making adjustments to the current structures. Such scenarios often describe how a certain target can be met cost-efficiently. Optimisation energy systems models such as TIMES are often used in this context. The TIMES model generator was developed under the OECD/IEA's Energy Technology Systems Analysis Program (ETSAP). TIMES is a technology rich, bottom-up model generator, which uses linear programming to produce a least-cost energy system, optimized according to a number of user-specified constraints, over the medium to long-term. It is used for "the exploration of possible energy futures based on contrasted scenarios". Normative scenarios also include transforming scenarios, often used in backcasting studies. The result of a backcasting study is typically a number of target-fulfilling images of the future, which present a solution to a societal problem, together with a discussion of the major structural changes that would be needed to reach the images. The WEO's 450 Scenario is a typical example of a transforming scenario. This scenario assumes a set of policies that bring about a trajectory of GHG emissions from the energy sector that is consistent with the goal of the limiting the rise in the long-term average global temperature to 2^{0}C, and illustrates how this might be achieved.

5.3 ENPAC TOOL FOR CONSTRUCTING ENERGY MARKET SCENARIOS FOR ASSESSING ECONOMIC PERFORMANCE AND GHG EMISSIONS REDUCTION POTENTIAL OF INTEGRATED BIOREFINERY INVESTMENTS IN INDUSTRY

Scenario consistency is very important, i.e. different energy market parameters must be clearly related to each other within a scenario (e.g. via key energy conversion technology characteristics and substitution principles). For constructing consistent scenarios, a calculation tool incorporating these inter-parameter relationships is essential. For this purpose, the Energy Price and Carbon Balance Scenarios tool (ENPAC) was developed by researchers at Chalmers for assessing the long-term impact of PI measures, as described in Axelsson et al (2009) and Axelsson & Harvey (2010). The tool was updated in 2014 (see Axelsson and Pettersson, 2014) and more recently in 2017 (see Axelsson, 2017). The environmental impact is restricted to Global Warming Potential. The frequent updates stem from (a) the pace of change of the international energy scene, as portrayed by the annual releases of the WEO reports; (b) new requirements and insights resulting from a number of research projects that have used the tool.

The purpose of the ENPAC tool is to compile insights from major international energy market modelling efforts as well as output from energy market and policy analyses such as World Energy Outlook and to make them available in a simplified form for industrial decision-makers. The main purpose of the tool is to investigate the economic performance and GHG emissions consequences of possible future energy project investments at an industrial process site, and can thus provide data about background system characteristics for prospective LCA studies. The tool adopts a consequential approach with system expansion to avoid impact allocation issues. Consequences of change in the surrounding system are assessed by making assumptions about possible marginal changes in the surrounding system as a result of changes at the process site. Based on these assumptions, the tool calculates energy prices for large-volume users based on possible future world market fossil fuel prices and relevant policy instruments (e.g. costs associated with emitting GHGs, incentives for increased use of renewable energy sources in the electric power market or increased use of climate-neutral fuels in the transportation market), and key characteristics of energy conversion technologies in the district heating and electric power sectors. Figure 5-1 provides an overview of the usage of ENPAC for generation of energy market scenarios for assessment of energy-related investments in industry.

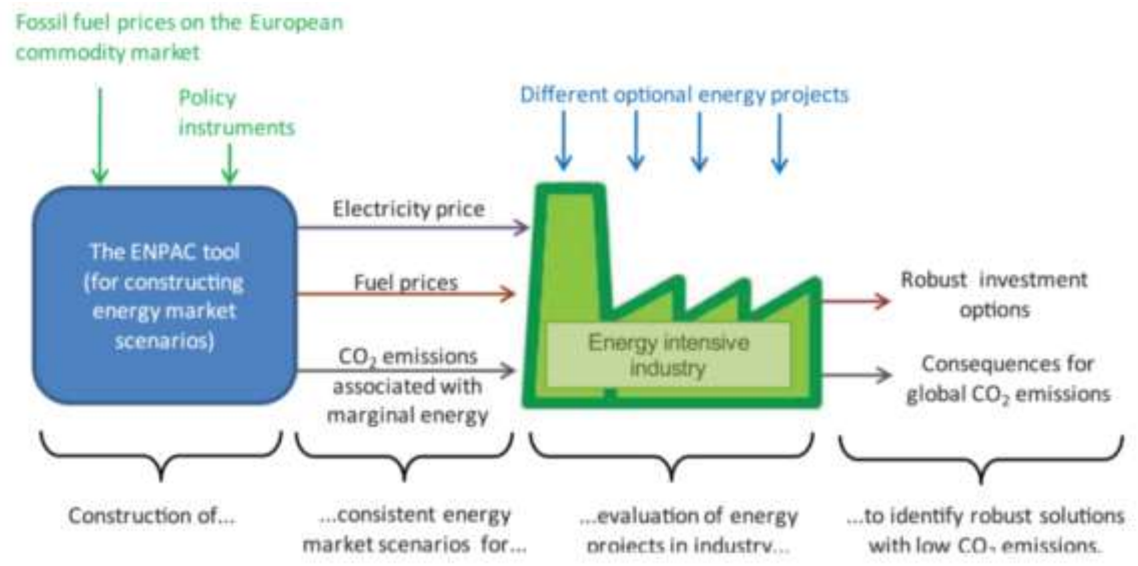

Figure 5-1. Overview of the usage of the ENPAC tool for generating energy market scenarios for assessment of energy-related investments in industry.

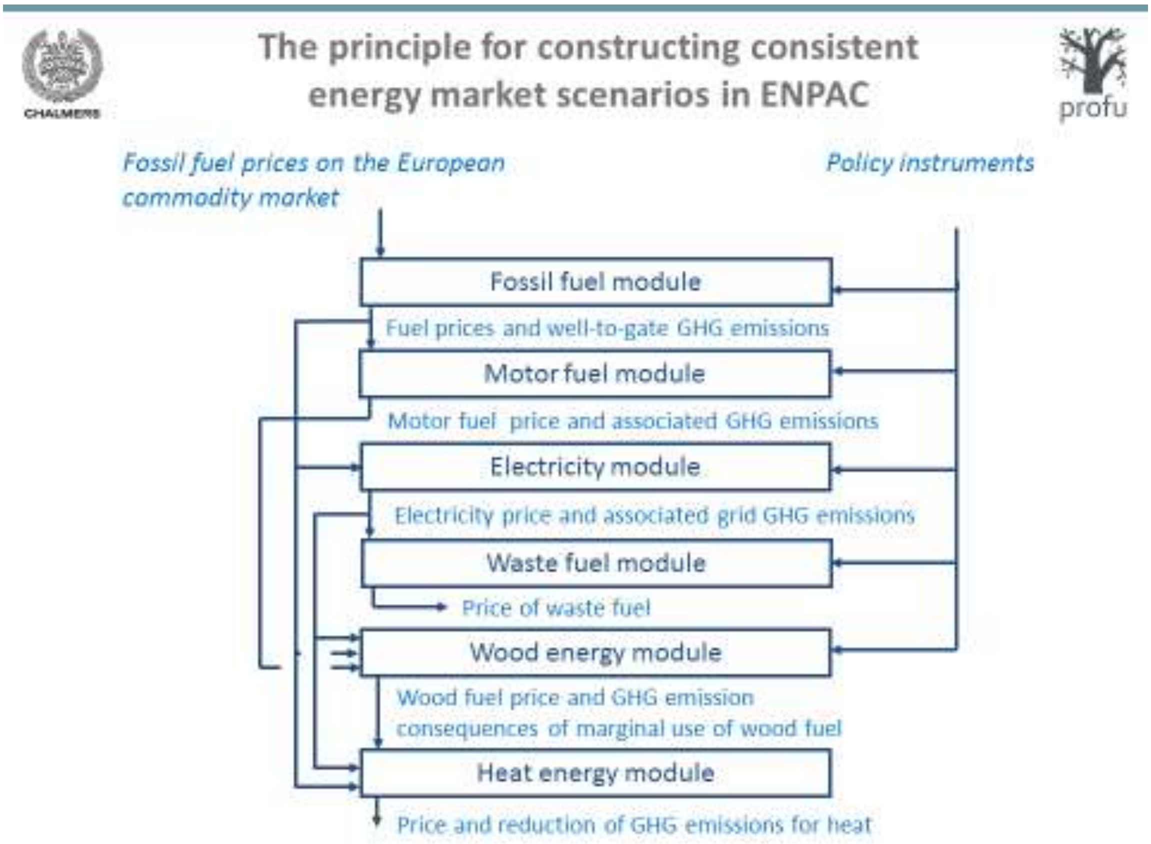

Figure 5-2. Overview of calculation modules in ENPAC for different energy market segments.

Figure 5-2 provides an overview of the calculation modules included in ENPAC for calculating energy carrier prices as well as GHG emissions for 6 different energy market segments. Hereafter these modules are presented very briefly. However, the reader is referred to previous work (Axelsson and Harvey, 2010; Axelsson and Pettersson, 2014; Axelsson, 2017) for a detailed presentation of the assumptions and models included in the modules.

- **Required user input data**: fossil fuel prices on the world energy market (crude oil, natural gas and steam coal) and charge for emitting CO_2. For markets with significant regional differences (such as the natural gas market), North European energy market data are considered. Other policy instruments can be included on an optional basis. In its current form, ENPAC includes the possibility to include production subsidies for fossil-free motor fuels and/or electric power generation.

- **Fossil fuel module**: calculates the market price for light and heavy heating fuel oil for industrial consumers based on the crude oil price, based on historical data. Includes costs for conversion and distribution. Steam coal and natural gas prices for industrial users are calculated in a similar way.

- **Motor fuel module**: Calculates product price at pump of conventional motor fuels (petrol and diesel) from crude oil price, based on historical data.

- **Electricity module**: identifies the base load power generation technology with lowest levelized COE for different future energy market conditions, i.e. the so-called build margin.

For near future conditions (2020), the Operating margin is identified. The selected technology depends on capital costs, fuel prices and policy instruments. Future electricity prices are assumed to be close to COE for base load build margin generation. CO_2 emissions related to electricity are assumed to be according to emissions of the load build margin power plant, as discussed in Elforsk (2006 & 2007) and Nordic Energy Research (2016).

- **Waste fuel module**: Calculates the willingness to pay (WTP) for waste fuel based on marginal cost for increasing waste incineration in a Waste-to-Energy (WTE) plant. The marginal WTE capacity is assumed to be CHP instead of heat only. Consequently, WTP for waste fuel depends on the electricity price and the marginal investment cost-
- **Wood energy module**: non-upgraded biomass fuel is an energy carrier that is often discussed when investigating future developments in the forest industry, e.g. as a residual product in a highly efficient pulp mill plant, or as feedstock for a future biorefinery plant. In order to quantify the economic value of or the GHG mitigation potential of this type of energy carrier, the ENPAC tool makes assumptions about the possible future marginal user of biomass fuel. ENPAC currently allows 2 possible marginal user categories: (1) co-firing with coal in a coal-fired power plant connected to the North European base-load power grid; (2) conversion to biofuel in a biorefinery. It is furthermore assumed that biomass is a limited resource, thereby the GHG mitigation impact can be calculated on the basis of the corresponding quantity of fossil fuel (coal or petrol/diesel fuel). However, this is a simplified model, in part because biomass markets are regional in nature, due to transportation costs, and in part because the marginal users of biomass vary from region to region. This module is thus in need of significant further development.
- **Heat module**: calculates WTP for excess heat delivery from an industrial plant to a district heating system based on the identified price setting technology in a representative heat market.

5.4 OVERVIEW OF PROCESS INTEGRATION STUDIES OF FUTURE BIOREFINERY CONCEPTS CONDUCTED USING ENERGY MARKET SCENARIOS GENERATED BY ENPAC AND COMPARISON WITH OTHER METHODOLOGIES FOR SIMILAR TYPES OF STUDIES

The ENPAC tool has been used extensively by researchers in the Industrial Energy Systems Analysis group at Chalmers. Holmgren et al (2016) use energy market scenarios to compare economic performance and carbon footprint of different integration options for gasification-based biofuel production systems producing synthetic natural gas, methanol, or FT (Fischer-Tropsch) fuels. The integration options considered are heat delivery to a district heating system or a nearby industrial process plant, or integration with infrastructure for CO_2 storage. Similar studies have been conducted for integrated gasification-based biorefinery options for oil refineries (e.g. Johansson et al., 2013), pulp and paper mills (e.g. Isaksson et al., 2012), bulk chemical production (Arvidsson et al., 2015) and district energy plants (Heyne and Harvey, 2013). The focus of these studies was to compare the performance of potential investments. Energy market scenarios can also be used for structured analysis of strategic investment decision making applied to biorefinery options. Examples of such analyses include the work of Jönsson et al. (2013) and Pettersson & Harvey (2012). Finally, energy market scenarios can also be used for prospective optimization studies of future strategic investments in biorefinery projects. For example, Svensson et al (2014) explored the potential value of flexibility in the planning of pulp mill energy and biorefinery projects and demonstrates how this value can be incorporated into models for optimal strategic planning of such investments. The paper discusses the requirements on the optimization models in order to adequately capture the value of flexibility. It is suggested that key elements of the optimization model are multiple points in time where investment decisions can be made as well as multiple scenarios representing possible energy price changes over time.

Energy markets scenarios generated using ENPAC have also been used by other Swedish research groups for investigating biorefinery opportunities. See e.g. Difs et al (2010) for investigation of biorefinery plants in a district heating system. However, a more common approach is to consider a single set of energy market parameters, and to conduct sensitivity analyses for a number of selected parameters. This is the approach adopted by e.g. Pettersson et al. 2015), Börjesson and Ahlgren (2010), and Hannula and Arpiainen (2015). Advanced investment planning tools for biorefineries have been developed recently by researchers at École Polytechnique de Montréal. In Dansereau et al. (2014), an integrated supply-chain planning framework for forest-industry biorefinery concepts is presented. It is based on optimizing a superstructure to help decision makers identify different supply-chain policies to adapt to different market conditions. It integrates revenue management concepts, activity-based cost accounting principles, manufacturing flexibility and supply-chain flexibility in a tactical model to maximize profit in a price-volatile environment. However, as in the previously mentioned research papers, the case study results presented build upon a single set of energy market parameters, and sensitivity analysis is performed for selected parameters.

Systematic methodology for ex ante assessment of biorefinery concepts has been developed by researchers at the Copernicus Institute of Sustainable Development at Utrecht University in the Netherlands (see e.g. Saygin et al, 2014 and Broeren et al, 2017). The approach used for scenario analyses builds in part upon consistency assumptions, however, standard sensitivity analyses are also included in the approach presented.

5.5 ILLUSTRATIVE EXAMPLE: COMPARATIVE STUDY OF FISCHER-TROPSCH (FT) PRODUCTION AND POST-COMBUSTION CO_2 CAPTURE AT AN OIL REFINERY: ECONOMIC EVALUATION AND GHG BALANCES USING ENPAC SCENARIOS

5.5.1 Introduction

This section summarizes the findings of the work of Johansson *et al* (2013a). The purpose is to highlight how ENPAC can be used for strategic long-term assessment of different development routes for energy efficiency improvements and GHG mitigation in an energy-efficient complex oil refinery.

Two new and promising low-carbon technologies for the oil refinery were chosen in the study:

- Case 1: Biomass-to-FT fuel production (Integrated with the refinery (a) and stand-alone facility (b))
- Case 2: Post-combustion CO_2 capture and storage of refinery CO_2 emissions.

In both alternatives, the FT syncrude refining is conducted in existing refining units, co-processed along with crude oil. The capacity of the refinery units is assumed to be sufficient; no changes to the refinery structure are necessary.

5.5.2 Methodology

Energy and mass balances were performed for both cases. For energy usage and excess heat estimations, process integration calculations were performed, both for the biorefinery plant itself and for the integrated system with the oil refinery.

Based on data and results from previous work by the authors (Johansson et al, 2013b & 2014), a prospective assessment was conducted in which the economic performance and reduction of GHG emissions associated with integration of a biomass-to-FT fuel process were compared with introduction of a post-combustion CO_2 capture plant at the case study refinery. The general methodology followed the steps outlined below:

- Definition of the studied system boundaries and the surrounding systems used for evaluation of the studied systems.
- Calculation of the current excess heat at the case refinery, by extracting the refinery process streams and flue gases that are currently cooled with utility (air and cooling water) based on information in Andersson et al (2013). The available excess heat is then assumed to be recovered and used as a heat source for driving the solvent regeneration unit in the post-combustion CO_2 capture plant.
- Identification of the heat demand in the refinery processes based on data and results in Andersson et al (2013). The heat demand is considered as a heat sink for excess heat from the biomass-to-FT process.
- Determination of energy balances including identification of available excess heat from a heat integrated FT syncrude production.
- Assessment of the possible potential for the two technologies to be heat integrated with the refinery.
- Calculation of the resulting energy balances after heat integration and comparison with the reference refinery.
- Identification of emission factors related to the surrounding systems (e.g. electricity generation and replacement of fossil-fuels) using future energy market scenarios generated with the ENPAC tool.
- Estimation of the investment costs (CAPEX) for process equipment.
- Prospective assessments of the net annual profit (including CAPEX and operating costs OPEX) and GHG emissions reduction compared to the reference refinery using different future energy market scenarios generated using ENPAC.

5.5.3 Use of ENPAC for generating energy market scenarios

The economic performance of the investments in the studied technologies and the associated impact on GHG balance were assessed using consistent energy market scenarios generated using the ENPAC tool. Note that the scenarios were generated using an earlier version of ENPAC in which the CO_2 charge and levels of fossil fuel prices were varied independently, in agreement with the structure of previous versions of energy futures presented in the IEA’s World Energy Outlook. The scenarios were based on combinations of different levels of fossil fuel prices and CO_2 charges. The fossil fuel prices represent different developments in the fossil fuel market, and the charges for CO_2 represent weak to strong ambitions to decrease CO_2 emissions. Four different scenarios were retained with a view to outlining possible cornerstones of the future energy market, see Figure 5-3.

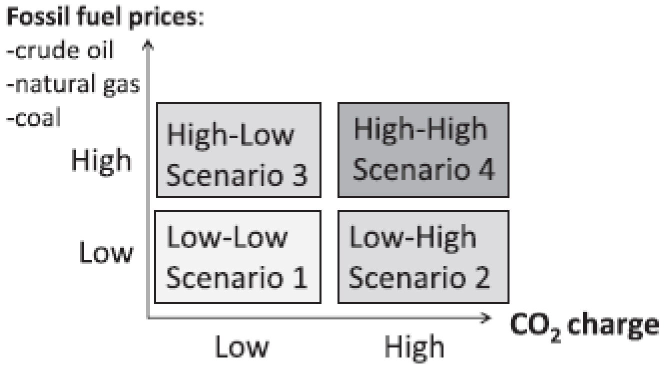

Figure 5-3. Energy market scenario structure.

The year 2030 was chosen for a preliminary assessment. In a more detailed study, estimations for several different years must be performed. The input data for the two levels of fossil fuel prices were taken from World Energy Outlook 2010 (OECD/IEA, 2010). The two levels of future charge for emitting CO_2 were taken to be the highest value and the mean value for 2030 presented in roadmap reports from the European Commission (2011) and Eurelectric (2009).

It was assumed that the high-volume user of wood fuel with the highest willingness to pay is the marginal price-setting user for wood fuel. In the scenario with a low charge for CO_2, FT facilities were assumed to have the highest willingness to pay for wood fuel, whereas coal power plants have a higher willingness to pay in scenarios with a high charge for CO_2. The level of support for renewable electricity and fuels were set to represent an average value for Europe at the time of the study. The energy market scenario data used in the study is presented in Table 5-1.

Table 5-1. Energy market parameters for the different scenarios. The prices are for year 2030.

Input data to ENPAC				
Fossil fuel price	Low-low	Low-high	High-low	High-high
- Crude oil (€/MWh)	43	43	62	62
- Natural gas (€/MWh)	32	32	40	40
- Coal (€/MWh)	7	7	11	11
CO_2 charge (€/tCO_2)	45	106	45	106
Support for renewable electricity (€/MWh$_{el}$)	20	20	20	20
Support for renewable fuel (diesel fuels) (€/MWh$_{fuel}$)	26	26	26	26
Support for renewable fuel (gasoline fuels) (€/MWh$_{fuel}$)	35	35	35	35
Scenario tool output	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Electricity price (€/MWh$_{el}$)	69	77	78	89
GHG from electricity generation (kg CO_{2eq}/ MWh$_{el}$)	259	259	805	259
Build marginal technology for electricity production	Coal w. CCS	Coal w. CCS	Coal w. CCS	Coal w. CCS
Price of low grade wood fuel (€/MWh$_{fuel}$)	28	49	38	53
Alternative user of wood fuel	FT CCS	Coal	FT CCS	Coal
Natural gas price* (€/MWh$_{fuel}$)	37	37	45	45
FT Diesel gate price (€/MWh$_{fuel}$)	69	86	90	107
FT gasoline gate price (€/MWh$_{fuel}$)	62	79	81	98

* Price on the European market inclusive transit and distribution costs.

5.5.4 Resulting net annual profit and GHG emissions for the studied cases

Figure 5-4 shows the system boundaries considered for calculating the net annual profit and the GHG emissions reduction potential for the different cases considered. As shown in the figure, the study adopted a Well-to-Wheel perspective, i.e. upstream emissions associated with biomass feed-stock harvesting and preparation are considered, as well as emissions at the plant site and emissions associated with end-use of the fuel.

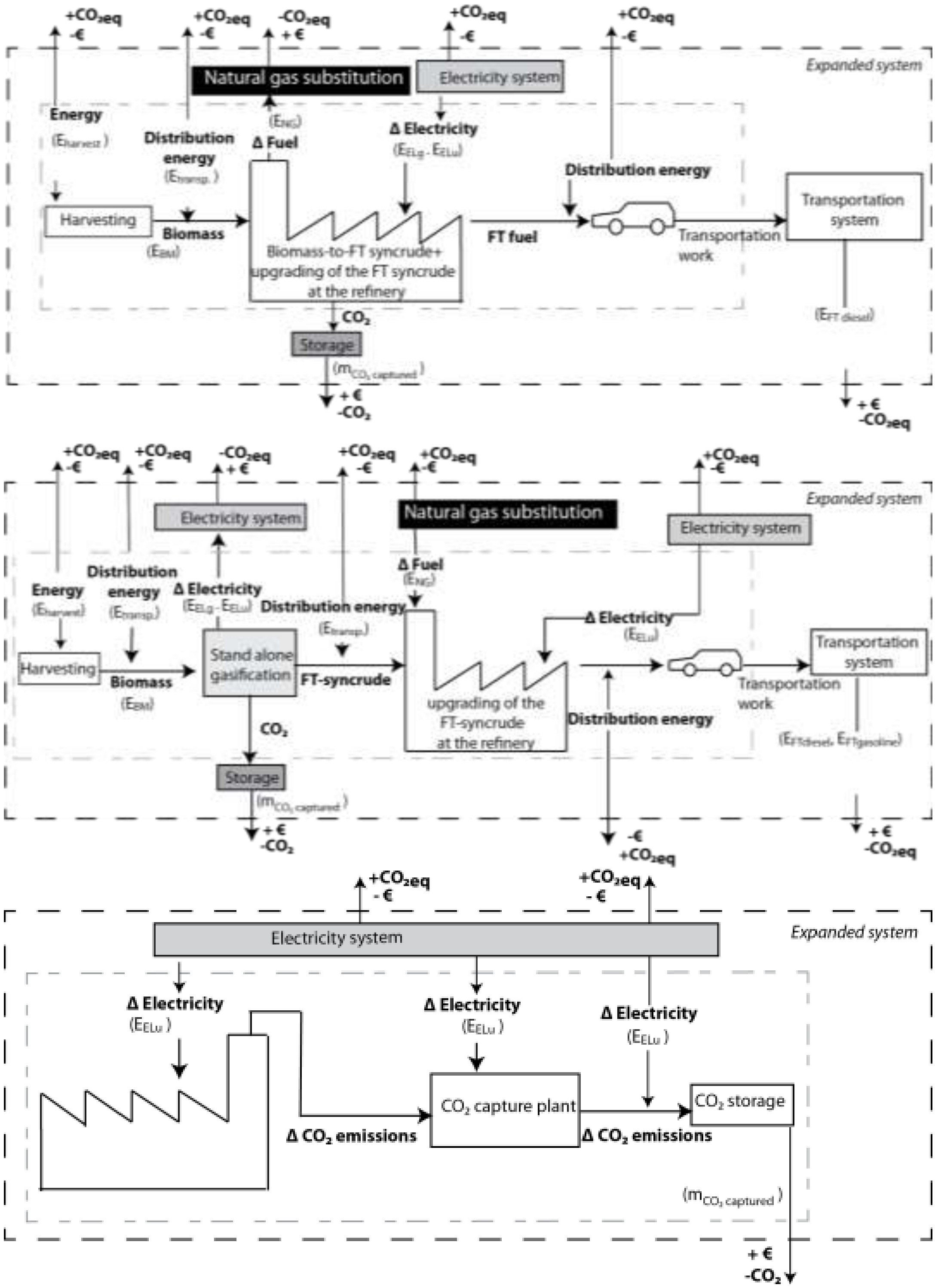

Figure 5-4. System boundaries for the systems analysis of the net annual profit and the GHG emissions.

Figure 5-5 presents the results for the studied cases under the four different energy market scenarios considered. The net annual profit and the global GHG emissions are presented as the change compared to the reference refinery.

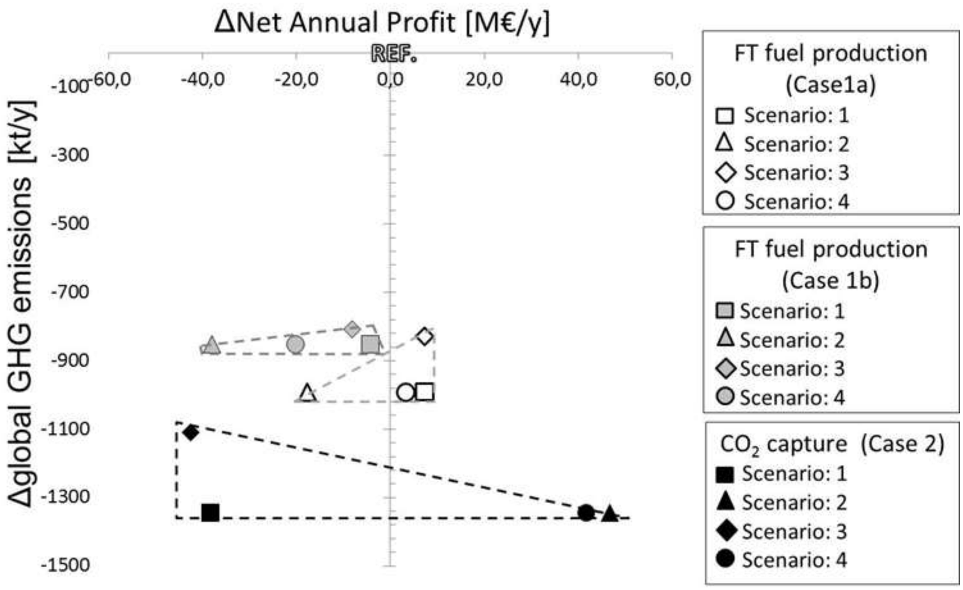

Figure 5-5 The net annual profit and global GHG emissions for the studied cases and the studied scenarios.

As expected, all the studied cases show a reduction in GHG emissions compared to the reference case (negative Δglobal GHG emissions). The marginal technology for electricity generation is the same for all studied scenarios, except for Scenario 3, and the resulting reductions of global GHG emissions are thus the same for these scenarios. Since all the studied cases have a net import of electricity, the increase in generation of marginal electricity will decrease the global GHG emission reduction. In Scenarios 1, 2 and 4 the marginal electricity generation technology is coal power plant with CCS, whereas in Scenario 3 the marginal electricity generation is coal power. For that reason, the global GHG reduction is greater in Scenarios 1, 2, and 4 where the GHG emissions associated with the marginal electricity is lower. The two levels of GHG emission reduction for all the studied cases are therefore related to the net electricity import, and thus the case with a small net electricity import will have the smallest difference between the two levels of GHG emission reductions (i.e. the stand-alone FT case). The CO_2 capture case has, not surprisingly, the largest global GHG emission reduction potential. The reduction is solely due to the capture of CO_2 from the refinery processes. The larger reduction in the integrated FT syncrude case compared to the stand-alone case is due to reduced natural gas usage. Furthermore, the stand-alone case generates more electricity. However, this does not affect the global CO_2 emissions as much as the amount of natural gas that could be saved in the integrated FT case in scenarios in which the marginal electricity generation is coal power with CCS.

In Scenarios 2 and 4, where a high charge for emitting CO_2 was assumed, CO_2 capture shows the largest net annual profit. It should however be noted that the level of the charge for CO_2 emissions is very high in these scenarios (106 €/t CO_2). CO_2 emission allowances constitute the only source of revenue in the CO_2 capture case, which makes this alternative very sensitive to the charge for emitting CO_2. For the CO_2 capture process to be profitable, the charge for emitting CO_2 must exceed the CO_2 avoidance cost. A rough interpolation shows that the CO_2 avoidance cost must exceed a value of around 75 €/t CO_2.

The heat integrated FT case is profitable in three of the studied scenarios (Scenarios 1, 2 and 4). In Scenarios 1 and 3, where a low charge for CO_2 was assumed, integrated FT fuel production shows the largest net annual profit. These scenarios are characterized by a lower price for wood fuel than in Scenarios 2 and 4. The biomass price is very high in Scenarios 2 and 4, but for Scenario 4 this is compensated by a high selling price for the FT fuels. The stand-alone FT case shows no profitability in any of the studied scenarios. The explanation is that the large amount of natural gas that can be saved in the heat integrated FT case generated more revenues than the extra electricity that is generated in the stand-alone case.

In summary and within the context of this study, if the charge for CO_2 is high then investing in a CO_2 capture plant is more profitable than investing in FT fuel production. However, a low or moderate charge for CO_2 means that investing in a heat integrated FT fuel production would be a more profitable alternative for a refinery than CO_2 capture.

5.5.5 Conclusions

The primary conclusions of the investigation were the following:

- A high charge for emitting CO_2 is essential for CO_2 capture to be profitable.
- A high charge for emitting CO_2 favours CO_2 capture, whereas a low charge for CO_2 favours FT syncrude production.
- Support for renewable fuel production is essential for FT syncrude production to be profitable.

Additional conclusions for the conditions and assumptions valid in this study are:

- Integrated FT syncrude production is most profitable in scenarios with a low wood fuel price. The stand-alone alternative does not achieve profitability in any of the studied scenarios.
- The CO_2 capture case is only profitable in scenarios with a high charge for emitting CO_2.
- Of the studied alternatives, CO_2 capture shows the greatest reduction in global GHG emissions.
- The results for all cases are sensitive to a change in the capital recovery factor, which is due to high investment costs.
- Without the option to capture and store the concentrated CO_2 stream in the FT process the potential for reduction in GHG emissions in the FT cases significantly decreases.

Based on the type of conclusions discussed above, an industrial board of directors can take strategic decisions about future integration of new technologies/systems. To do that, the board must decide about general assumptions regarding e. g. future developments of energy prices and policy instruments, although not in detail. The general trends discussed above should form a firm basis for strategic decisions. If a technology/system is found to be ”robust”, i.e. with a suitable level of profitability and/or emissions reduction in all or a majority of scenarios, that solution should be of interest to study further. In this case the integrated FT plant was found to be nearly robust (in 3 scenarios out of 4). Conversely, the stand-alone FT was found to be ”negatively robust”, i.e. not profitable in any of the scenarios, and can therefore be ruled out for further consideration.

6 COST AND GHG BALANCE CALCULATIONS FOR SELECTED BIO-METHANE PRODUCTION CONCEPTS FROM THE “METDRIV” PROJECT USING INPUT DATA GENERATED USING THE ENPAC TOOL

6.1 BACKGROUND

In the METDRIV project (see Börjesson *et al*, 2016), the energy, greenhouse gas emissions (GHG) and cost performance of existing and potential new methane-based vehicle systems solutions were analysed. Two different conversion technologies were included; anaerobic digestion of organic waste feedstock, and thermal gasification of forest residuals. The input data used in METDRIV were based on average prices/costs and GHG emission factors valid at the time of the study for the surrounding supply systems. This section illustrates how the results change if new input data based on results generated by the ENPAC (Energy Price and Carbon Balance Scenarios) tool developed by Chalmers and Profu are used instead. The ENPAC data include future, estimated marginal prices and GHG emission factors for possible future conditions in the surrounding supply systems, as required for prospective consequential analysis. Thus, the overall aim of this case study is to illustrate the importance of transparently describing the assumptions made in systems studies regarding the type of input data that are used, and the corresponding consequences if other types of input data are chosen.

The METDRIV project investigated a number of alternative production routes for producing bio-methane. The different routes were assessed with respect to their Well-to-Tank (WTT) and Well-to-Wheel (WTW) performance. The energy market scenarios generated by ENPAC are primarily intended to be used for assessing investment options at an industrial process site, i.e. Well-to-Gate (WTG) performance. Furthermore, the ENPAC tool was developed considering material and energy flows of relevance for large-scale industrial processes and does not contain information about organic waste fractions of municipal solid waste. The work therefore focused on the WTG performance results for a single bio-methane production technology, namely a large-scale thermal gasification plant based on oxygen-blown, circulating fluidized bed gasification technology producing 200 MW of bio-methane from 320 MW of forest residuals (50% moisture content by weight). The main material and energy input/output flows of relevance are summarized in Table 6-1, based on data provided in the METDRIV report (Börjesson *et al*, 2016), which were in turn based upon a feasibility study performed by E.ON (Fredriksson Möller *et al*, 2013).

Table 6-1. Main Input/Output flows for the thermal gasification-based bio-methane plant investigated in the METDRIV study. Note: the plant is assumed to operate for 8000 h/yr. However, district heat delivery is only assumed to be possible for 5000 h/yr.

INPUT FLOWS	
Biomass (forest residuals, 50% m.c.)	320 MW / 2560 GWh/yr
Electric power for ASU, feedstock handling and product gas compression	24 MW / 192 GWh/yr
OUTPUT FLOWS	
Bio-Methane	200 MW / 1600 GWh/yr
On-site electric power generation	16 MW / 128 GWh/yr
District heat delivery	10 MW / 50 GWh/yr

6.2 GHG EMISSIONS PERFORMANCE ANALYSIS

In this section, the results from the METDRIV project regarding methane production from thermal gasification of forest residuals fuels are evaluated from a GHG perspective using a consequential approach with marginal GHG emission factors. The system boundaries adopt a well-to-gate (WTG) perspective, thus excluding distribution of the methane to filling stations as well as use of the fuel in internal combustion engines for transportation purposes. The original GHG calculations in METDRIV adopted an attributional LCA approach with mean values of GHG emissions from the energy carriers utilized, such as electricity, wood fuels, etc. In this case study, the calculations in METDRIV are revised using marginal values of GHG emissions instead, based on input data generated using the ENPAC tool, which are in turn based on two of the scenarios presented in the 2016 edition of IEA's World Energy Outlook (OECD/IEA, 2016a). Table 6-2 provides an overview of the GHG emission factors associated with the bio-methane plant input/output flows. For comparison, the GHG emission factors utilized in the original calculations in the METDRIV study are also shown.

Table 6-2. GHG emission factors for years 2020, 2030 and 2040, for selected energy carriers in the ENPAC tool (kg CO2/MWh)*. For comparison, GHG emission factors utilized in the METDRIV project are also shown.

Energy carrier	2020		2030		2040		METDRIV
	np	450	np	450	np	450	
Electricity	856	856	0	0	0	0	126
Wood fuels alt. 1	9	9	9	9	9	9	14
Wood fuels alt. 2	119	119	127	401	127	401	----
Diesel	289	289	289	289	289	289	290
NG	248	248	248	248	248	248	248
Gasoline							

* GHG emission factors for electricity refers to build margin. The scenarios are as follows: (i) np: World Energy Outlook 2016 – new policies, and (ii) WEO-450: World Energy Outlook 2016 – 450 ppm.
Wood fuels alt. 1: direct emissions from collecting and transport. Wood fuels alt. 2: indirect marginal emissions including alternative use of the wood fuels replacing various fossil fuels. The METDRIV data include Nordic electricity mix and only direct emissions from wood fuel collecting and transport (no soil carbon changes etc).

The well-to-gate (WTG) emissions presented in the original METDRIV study are based on the calculation methodology applied in the EU's Renewable Energy Directive (RED). The GHG emission factor for electricity thus represent the Nordic electricity mix (see Table 6-2) and the emission factors for wood fuels (logging residues) correspond to alternative 1, i.e. emissions associated with collection and transport operations are included but potential changes in soil carbon content etc., are excluded.

6.3 RESULTS AND CONCLUSIONS OF THE GHG EMISSIONS PERFORMANCE ANALYSIS

Figure 6-1 shows WTG GHG emissions from the methane production systems calculated using marginal GHG emission factors generated by the ENPAC tool for two future scenarios (see Table 6-2). For comparison, the WTG GHG emissions calculated in the original METDRIV study are also shown, as well as the fuel-cycle emissions of petrol and gasoline according to RED. A conclusion from Figure 6-1 is that the use of ENPAC data (alternative 2), instead of current average data regarding GHG emissions, will have a significant impact on the GHG performance results of the biomass-based methane. The GHG emissions will be 10-30 times higher for wood fuel-based methane when the indirect marginal emissions including alternative use of the biomass replacing various fossil fuels are included (i.e. alternative 2 compared to alternative 1). Also, the GHG emissions will be 33% lower than fossil liquid fuels regarding all the WEO-new policy scenarios, whereas the GHG emissions will be twice as high for the WEO-450 scenarios 2030 and 2040, compared to fossil liquid fuels. When only direct emissions are included (alternative 1), the ENPAC data leads to similar emissions as the METDRIV study and equivalent to 6-7% compared with fossil liquid fuels.

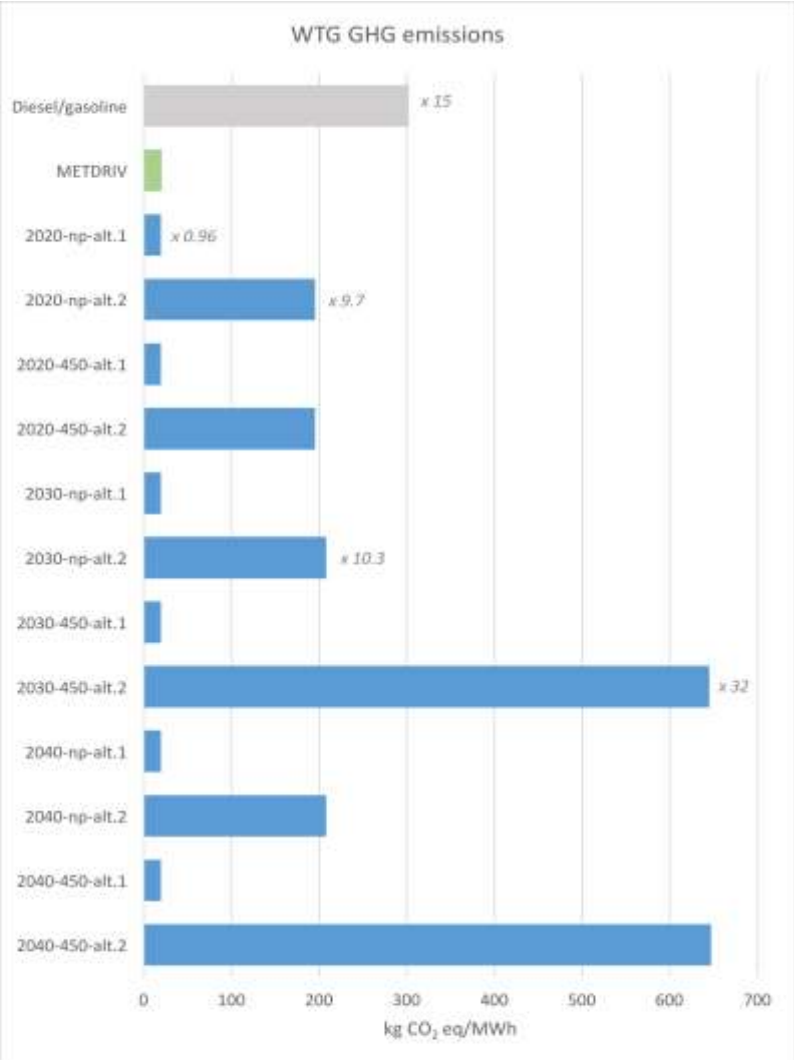

Figure 6-1 Well-to-gate (WTG) GHG emissions recalculated from the original METDRIV study using GHG data from the ENPAC tool.

6.4 ECONOMIC PERFORMANCE ANALYSIS

Table 6-3 shows the cost factors used in the analysis. The cost factors for the METDRIV project reflect average prices/costs valid at the time of the study (i.e. 2015). Note also that Swedish policy instruments in 2015 granted a premium to all production of electric power from renewable energy sources. Therefore, costs and revenues for all on-site power usage and power export are treated separately. For ENPAC calculations, only the net power balance is considered. As discussed previously, the ENPAC electricity price calculations adopt a "build margin" perspective, and the market price is assumed to reflect the base load build margin technology with the lowest levellised cost of generation among a pool of candidate technologies.

Table 6-3 Cost factors for years 2020, 2030 and 2040, for selected energy carriers in the ENPAC tool (€/MWh). For comparison, cost factors utilized in the METDRIV project are also shown. NOTE: cost data reported in METDRIV in SEK were converted to € using exchange rate 9.37 SEK/€.

Energy carrier	2020		2030		2040		METDRIV (2015)
	np	450	np	450	np	450	
Electricity (purchased)	52	51	61	61	66	71	53,4
Electricity (sold to grid)	42	41	51	51	56	61	42,7
Wood fuel	21	19	28	41	35	54	21,3
District heat	26,21	23,85	34,44	49,74	42,68	65,03	26,7
Natural gas	34	33	48	58	55	67	38*
CO_2 charge** (€/tonne)	18	18	33	90	45	126	n.r.

*The METDRIV study considered the market prices for CNG and LBG, which are not relevant for a WTG study. The price indicated in the table reflects the average price paid by large volume industrial consumers in Sweden in 2015, which is assumed to be close to the gas grid wholesale price in ENPAC.

**The CO_2 charge is an indicative value of the cost associated with emitting fossil CO_2. It is assumed that this value applies to all user categories in all sectors of the economy. This cost is embedded in all other ENPAC cost factors, where applicable.

In ENPAC, the market price for low grade wood fuel is based on the estimated price a reference alternative user is willing to pay compared to a (fossil-based) substitute. This assumption is comparable to alternative 2 in the GHG emissions calculations, and it reflects a situation in which biomass is a limited resource, leading to rapidly increasing wood fuel prices, especially in the 450 ppm scenario. It is beyond the scope of this work to discuss the validity of the wood fuel price development model in ENPAC. However, it should be noted that the price development for the 450 ppm scenario indicates a price level in 2040 that is approximately 2.5 higher than current price levels. Such an increase is much higher than price increases discussed by a number of detailed studies of possible development of the Swedish low-grade wood fuel market, even for scenarios based upon substantial development of the Swedish bio-based economy (see e.g. Pöyry, 2016).

The revenue from sales of district heat is based upon an alternative heat production cost for heat produced in a boiler (85% efficiency) fired with low grade wood fuel, and 15 SEK/MWh operation and maintenance costs.

The performance indicator selected for the analysis is the break-even production cost for bio-methane (in SEK/MWh). Important input data for the analysis are listed in Table 6-4. The METDRIV calculations were performed using the annuity method. The capital costs were annualized using the economic lifetime and interest rate factors listed in Table 6-4. The annual cash flows were assumed to be constant during the lifetime of the plant, and were estimated based on the OPEX costs listed in Table 6-4, and the monetary values of the input/output flows listed in Table 6-1 were estimated using the METDRIV cost factors listed in Table 6-3.

Table 6-4. Input data for the economic performance analysis of a large-scale bio-methane production plant. NOTE: cost data reported in METDRIV in SEK was converted to € using exchange rate 9.37 SEK/€.

CAPITAL COSTS	
Plant investment costs	480 M€
Economic lifetime and interest rate	25 years; 6%
OPERATION COST DATA	
OPEX (incl. catalyst, personnel and maintenance)	17,1 M€/yr
Annual operating time	8000 h/yr
District heat delivery	5000 h/yr

The ENPAC based calculations were performed using the net present value (NPV) method. This was necessary since the cost factors associated with energy carriers are assumed to change over the lifetime of the plant. The analysis assumes overnight construction of the plant in 2018, and steady-state operation of the plant from 2019 to 2043. The annual cash flows are estimated in the same way as for the METDRIV calculations. However, the cash flows vary from year to year. The cost factors listed in Table 6-3 are assumed to vary linearly during periods 2019-2030 and 2030-2043, respectively. The annual change (absolute value) of the value of the produced bio-methane is assumed to vary in the same way as natural gas in Table 6-3. The break-even production cost calculations can thus be performed by estimating the value of the bio-methane gate sales price that yields a zero value for the NPV of the investment.

6.5 RESULTS AND CONCLUSIONS OF THE ECONOMIC PERFORMANCE ANALYSIS

The results (see Figure 6-2 below) show clearly that the required break-even sales gate price for bio-methane is substantially higher than the comparable market price for natural gas. It can be noted that compared to the simplified annuity method calculations performed according to the METDRIV study, the more detailed NPV calculations do not offer any significant new insights regarding the relative additional production cost of bio-methane compared to natural gas. However, the economic analysis illustrates the impact of significant possible variations of key cost factors resulting from the ENPAC scenarios. The significant increase over time of the charge for emitting fossil CO_2 leads to a major increase of the market price of natural gas, but it also leads indirectly to a significant increase of the cost of the biomass feedstock for the bio-methane plant. It should also be noted that the biomass feedstock is the main cost driver in the calculations, thus the cost factors associated with the other input/output flows to the plant do not affect the results to any noticeable extent in this specific case.

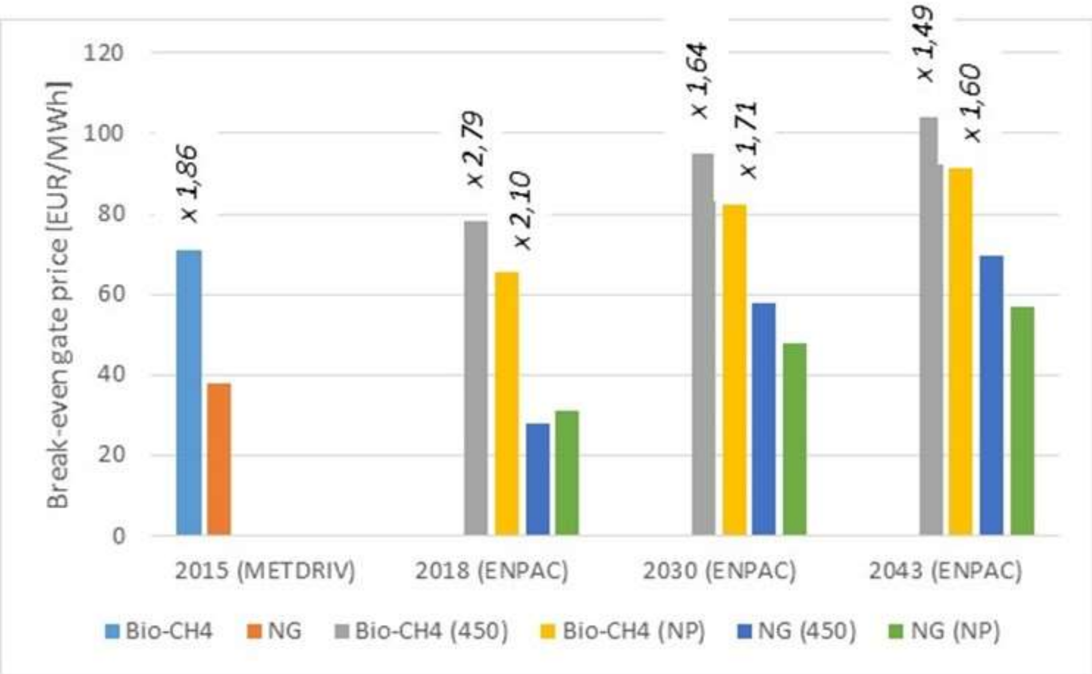

Figure 6-2. Break-even gate sales price for bio-methane (Bio-CH4) calculated with METDRIV and ENPAC data (NP and 450 scenarios). Note that for the ENPAC calculations, the results show the break-even gate sales price over the lifetime of the plant. The market price of natural gas (including costs for CO_2 emissions) are shown for comparison.

Table 6-5 presents cost breakdown results per produced MWh of bio-methane. The table clearly shows the impact of the rapidly increasing cost of the biomass feedstock in the different ENPAC scenarios, especially the 450 scenario. It can also be noted that the feedstock cost dominates the total OPEX costs. The table also shows that the assumptions used in calculations lead to a break-even bio-methane gate price that is the same as the total OPEX in 2043 in the 450 ppm scenario, which is due to assuming that the price development for bio-methane will follow the same price increments as natural gas, and that NPV calculations heavily discount cash flows in the distant future.

Table 6-5. Cost breakdown for the break-even gate sales price for bio-methane according to METDRIV and ENPAC calculations. All costs are expressed in €/MWh$_{biomethane}$.

	METDRIV	ENPAC NP Scenario			ENPAC 450 Scenario		
	2015	2018	2030	2043	2018	2030	2043
Feedstock	34,15	31,36	44,8	59,36	23,36	65,6	92,64
Other operating costs	13,18	11,91	12,04	11,96	12,05	11,56	11,46
TOTAL OPEX	47,33	43,27	56,84	71,32	35,41	77,16	104,10
Break-even Bio-methane gate price	70,81	65,49	82,29	91,39	78,14	94,94	104,04

7 CONCLUSIONS AND OUTLOOK FOR FURTHER WORK

This work aimed at compiling a state-of-the-art report on methods and approaches for assessing new biofuel production concepts in a long-term perspective. The participating research groups were Energy Sciences at Luleå University of Technology, Environmental and Energy Systems Studies at Lund University, Environmental Systems Analysis at Chalmers, and Industrial Energy Systems Analysis at Chalmers. Together, these groups constitute a significant part of the Swedish research expertise in the field of development and application of methods and tools for assessing the viability of future large-scale biofuel production technologies and systems.

The methods and tools that are commonly used to assess the viability of future large-scale biofuel production concepts include Techno-Economic Assessment (TEA) and Life Cycle Assessment (LCA). The main focus of the report was to provide an overview of the current research status of these analysis methods based on ongoing research within the participating groups, and to highlight important methodological choices and necessary assumptions related to application of TEA and LCA methods and tools for assessing biofuel production processes. The report also presents a series of case studies based on earlier work in the participating groups, quantifying the possible magnitudes of differences in results regarding economic performance and carbon footprint of future biofuel production processes, depending on differences in assumptions regarding conditions in the surrounding system. Many of the case studies illustrate the importance of a long-term approach for assessing both the economic and climate consequences of possible future changes in surrounding system conditions with respect to implementation of biofuel production concepts.

One key insight of the study was that traditional TEA studies are increasingly being expanded to include a number of environmental impacts that have conventionally been addressed by LCA studies. There is therefore a clear need for increased collaboration and data exchange between many R&D stake-holders, including biorefinery technology and process developers, value chain modellers, TEA and LCA practitioners and large-scale energy and material system modellers. This work made a significant step in this direction by clearly establishing the potential strength of prospective TEA and LCA in combination with scenarios describing possible future developments of the background energy system in which future biofuel production systems will operate. The ENPAC (Energy Price and Carbon Balance Scenarios) tool was presented. This tool was developed at Chalmers for generating consistent sets of future energy market prices and carbon emission factors that can be used in prospective TEA and LCA studies. The ENPAC tool was developed with the aim of compiling results and insights from major energy systems modelling studies (such as the International Energy Agency's annual World Energy Outlook study), and organizing these results and insights into relevant and significantly different cornerstone energy markets scenarios structured in a way that is useful for strategic decision makers in industry. The scenarios presented in the report show clearly that key parameters of relevance for assessing the economic and climate performance of biorefinery concepts can vary significantly more than the standard +/-30% often considered in sensitivity analyses. The scenarios allow decision makers to conduct packaged sensitivity analyses and to identify robust decision options, i.e. concepts that perform satisfactorily for a range of scenarios.

A case study was conducted with the purpose of illustrating the powerful potential of combining techno-economic analyse with prospective LCA in combination with future energy market scenarios generated using ENPAC. The case study example was one of the bio-methane production routes investigated in the METDRIV project that investigated methane production and usage as vehicle fuel adopting a a well-to-wheel perspective (see Börjesson et al, 2016). The large-scale gasification-based production route was re-assessed using a combination of state-of-the-art prospective TEA and LCA background energy system scenarios. The METDRIV project analysed the energy, greenhouse gas emissions (GHG) and cost performance of existing and potential new methane-based vehicle systems solutions. The input data used in the original METDRIV study were based on average prices/costs valid at the time of the study, as well as GHG emission factors valid at the time of the study for the surrounding supply systems. This work investigated how the results are affected by adopting new input data reflecting possible energy market development pathways generated by the ENPAC tool. Using this data it was possible to perform economic analysis using the net present value method to discount annual cash flows for the lifetime of the plant. For the production route that was selected, the results show clearly that assumptions regarding greenhouse gas emission factors related to increased use of biomass are of utmost significance, and that there is a clear need for further work in this area. The economic analyses illustrate the impact of significant possible variations of key cost factors. The significant increase over time of the charge for emitting fossil CO_2 leads to a major increase of the market price of natural gas, but it also leads indirectly to a significant increase of the cost of the biomass feedstock for the bio-methane plant. It should also be noted that the biomass feedstock is the main cost driver in the calculations, thus the cost factors associated with the other input/output flows to the plant do not affect the results to any noticeable extent in this specific case.

In conclusion, this work clearly established that there is a need for prospective assessment methods which address the related challenges arising from the lack of detailed data about future technologies, and lack of data about the background systems in which these technologies may operate. In traditional TEA and LCA studies, potential future changes of key parameters are often included indirectly by conducting sensitivity analysis, but there is a clear need to make such sensitivity analyses more “future based” and clearly discuss and use potential future changes in key parameters based on input data from e.g. energy system modelling results etc.

Some major challenges that remain to be addressed when developing scenarios for the “background” energy system are as follows:

- Handling the possible consequences of future limited biomass availability on biomass feedstock prices and emission factors. This is particularly challenging given that biomass can be used both as fuel in the energy sector and as feedstock in the basic material sector, thus price-setting mechanisms as well as climate consequences of biomass usage are characterized by complex interdependencies between sectors.

- Handling future development of the electric power grid, with increasing share of intermittent energy supply, as well as other large-scale grid energy systems (e.g. district heating) in a carbon-constrained world

- Considering integration issues. Large-scale biorefinery concepts are likely to be co-located at existing industrial sites, enabling synergy effects with respect to integration of material and energy flows. However, the host industrial processes themselves will also evolve in reaction to policy instruments, and it is important that prospective studies consider such changes as well as the changes in the surrounding energy system.

Other issues that should be addressed in further work include the following:

- System boundary issues, in particular methodology differentiation for conduction of long term sustainability assessments of fossil-free fuel production concepts for individual plants, as opposed to assessments for complete industrial sectors.
- Development of strategies and guidelines for establishing cut-offs when conducting consequential analysis of implementing biorefinery concepts, without risking to capture major impacts on economic performance and carbon footprint.

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